GE Aircraft Engines

UHB ENGINE FAN BROADBAND NOISE REDUCTION STUDY

Final Report Prepared for

National Aeronautics and Space Administration
Lewis Research Center
Contract NAS3 26617
Task Order 3

By

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SUMMARY

A study has been completed to quantify the contribution of fan broadband noise to advanced high bypass turbofan engine system noise levels. The result suggests that reducing fan broadband noise can produce 3 to 4 EPNdB in engine system noise reduction, once the fan tones are eliminated. Further, in conjunction with the elimination of fan tones and an increase in bypass ratio, a potential reduction of 7 to 10 EPNdB in system noise can be achieved. In addition, an initial assessment of engine broadband noise source mechanisms has been made, concluding that the dominant source of fan broadband noise is the interaction of incident inlet boundary layer turbulence with the fan rotor. This source has two contributors, i.e., unsteady lift dipole response and steady loading quadrupole response The quadrupole contribution was found to be the most important component, suggesting that broadband noise reduction can be achieved by the reduction of steady loading field-turbulence field quadrupole interaction. Finally, for a controlled experimental quantification and verification, the study recommends that future broadband noise tests be done on a simulated engine rig, such as the GE Aircraft Engine Universal Propulsion Simulator, rather than testing on an engine statically in an outdoor arena. The rig should be capable of generating forward and aft propagating fan noise, and it needs to be tested in a large freejet or a wind tunnel.

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1.0 INTRODUCTION

The projected growth of world commercial aircraft operations suggests that air traffic and passenger-miles will increase significantly by the turn of the century. Many airport operators and rule-making organizations feel that the current FAR36 Stage 3 community noise limits may not be sufficiently stringent to preclude significant community annoyance around airports. In addition, many airports around the world have already imposed their own noise-based operating restrictions in terms of operating quotas, landing fees, or night-time curfew limits. These local airport noise restrictions are usually more stringent than the FAR36 Stage 3 limits, and generally speaking, although the metrics may be different, they typically amount to an equivalent of 3 to 7 EPNdB greater stringency than FAR36 Stage 3 certification limits.

In preparation for the need for new noise reduction technology, NASA has established noise reduction goals for the Advanced Subsonic Transport Technology Program of 3 to 5 EPNdB by 1997 and 10 EPNdB by the year 2000. These goals are ambitious and aggressive, and, although they appear to be technically feasible, require the identification and development of new technology noise reduction concepts that allow the achievement of these noise reduction goals without severe increases in investment and operating cost. In fact, the engines of the future must be quieter *and* cheaper to buy and operate, in order to provide sufficient incentive for airlines to buy them in sufficient quantity to make it profitable enough for the engine manufacturers to produce them.

Aircraft propulsion systems for future applications are likely to have higher bypass ratios, say 8 to 12:1, compared to today's engines, which have bypass ratios in the range of 2 to 6:1 [1]. The trend toward higher bypass ratios, spurred by potentially large gains in fuel economy, implies that the fan component of the the propulsion system is likely to be the major noise source. A significant amount of aircraft turbofan noise work has been published in the past which addresses the understanding, control, reduction, and suppression of the *fan tone noise*. Several review publications, e.g. reference [2], available in the literature have summarized fan blade passing frequency harmonic tone noise and multiple pure tones of shaft harmonics related to supersonic fan tip speeds. Several articles have been published in the 1960's and 1970's [3-9], which specifically addressed *fan broadband noise*, usually as blade or vane response to turbulence, and several models were proposed based on the fundamental concept of blade lift fluctuations produced by response to turbulent gusts. Fan rig and engine experiments were carried out and empirical correlations were also developed [10-14]. However, until recently, the majority of research and development in fan noise since the 1970's has been focused on tone harmonics, especially unducted rotor and propellor tone noise.

The recent interest in Ultra-High Bypass (UHB) engine development has sparked a renewal in the importance and impact of fan broadband noise on the total engine system noise levels. Some preliminary calculations indicated that, for a typical modern turbofan, if one could completely eliminate all fan tones, the total system noise would only be reduced by 0.5 to 1.5 EPNdB, depending on the operating condition. The implication was that fan broadband noise is setting a "floor" to significant noise reduction advances, and ways must be found to reduce broadband noise as well, or the methods currently being developed for tone noise reduction will have little practical benefit.

In a previous study contract, "UHB Engine Aeroacoustic Study," NAS3-25269 Task Order 4, reference [1], GE identified candidate Ultra-High Bypass (UHB) engine concepts which provided the best reduction opportunities with the least economic penalties. The study also quantified the effect of bypass ratio selection on the acoustics and economics of advanced UHB engine concepts. Four single-rotation fan engine designs were studied, with design fan pressure ratios of 1.3, 1.45, 1.6, and 1.75. These engines were assumed to all have the same (advanced) core technology, i.e., they all had the same overall engine cycle pressure ratio, compressor exit temperature and high-pressure turbine inlet temperature design points. The study engines developed in this previous effort were felt to be a good database from which to carry out an evaluation of the importance and contribution of fan broadband noise to the the total engine system noise levels for engines of the future, e.g., year 2005 technology product introduction.

An important factor in the engine design decision process is to identify the noise reduction potential, and how much of the identified noise reduction required needs to be achieved by advances in noise source reduction, by suppression technology, and by the "natural" noise reduction through engine cycle (e.g., BPR) changes. Noise source reduction requirements can be further broken down into component noise (e.g, fan, core, jet turbine) source reduction requirements. For example, on high bypass engines, fan noise is a dominant noise source, composed of the fan blade-passing frequency tone and its higher harmonics, broadband noise, and multiple-pure tone or "buzz-saw" noise at (supersonic tip speeds). The question is then how much is contributed by the fan broadband noise toward the total system noise, and how much is the potential benefit for system noise reduction if broadband noise level is lowered. A corollary question to be answered is how much potential benefit of fan broadband noise reduction is realized if the tone levels are also reduced, vs. not reducing the tone levels. Finally, if fan broadband noise is determined to be a significant contribution to engine system noise levels and deliberate means for reducing it are required, then the important mechanisms responsible for fan broadband noise must be identified, understood, and the controlling parameters must be quantified.

2.0 OBJECTIVES

The major objectives of the present study were as follows: (1) to assess the fan broadband noise contribution to representative UHB engine system noise levels; (2) to establish the impact of reducing the fan broadband noise on total system noise as a function of engine Bypass Ratio, (3) identify candidate broadband noise generation mechanisms and their controlling parameters; (4) establish order-of-magnitude relative contributions due to these mechanisms; and (5) to develop an integrated analytical and experimental program plan that provides for both diagnostic evaluation of broadband noise mechanisms and the tools for identification of broadband noise reduction concepts.

3.0 APPROACH

3.1 UHB System Noise Impact

A parametric study was conducted to evaluate the influence of fan broadband noise on representative UHB engine total system community noise. The UHB engines selected for assessment were the four single-rotation turbofans reported in the UHB Engine Aeroacoustic Study contract final report (NAS3-25269 Task Order 4) reference [1]. An existing GE Aircraft Engines Flyover Noise System procedure called 'FAST' was employed, as described in reference [1], to predict the community noise levels of the four UHB engine cycles. The design bypass ratios for these four engines were 5.94, 7.75, 9.81, and 15.75. The corresponding design fan pressure ratios are 1.75, 1.6, 1.45, and 1.3. These study engines were designated in reference [1] as S75, S60, S45, and S30, respectively. A table of key engine cycle parameters is given in table 1. Engine preliminary cross-section sketches, from reference [1], are shown in figures 1a-d. The impact of broadband noise reduction on overall system noise levels were evaluated for three different scenarios, depending on how the broadband noise level reduction was implemented. The 'FAST' code separately predicts fan tones and broadband noise, so the effects of independently reducing the fan tones and the broadband noise could be evaluated.

The first scenario examined was to arbitrarily but parametrically reduce fan broadband noise levels by 1, 3, 5, and 10 dB at all frequencies and emission angles, without affecting other noise generation mechanisms or sources. The second scenario examined was to reduce both fan tones and broadband noise levels by these same amounts. The final scenario studied was to remove the fan tones altogether from the fan spectra, and then lower the fan broadband noise again by the above incremental amounts. In addition, because the four UHB engines used for the study have different cycles (BPR and FPR), the impact of cycle change on noise was also included in the study.

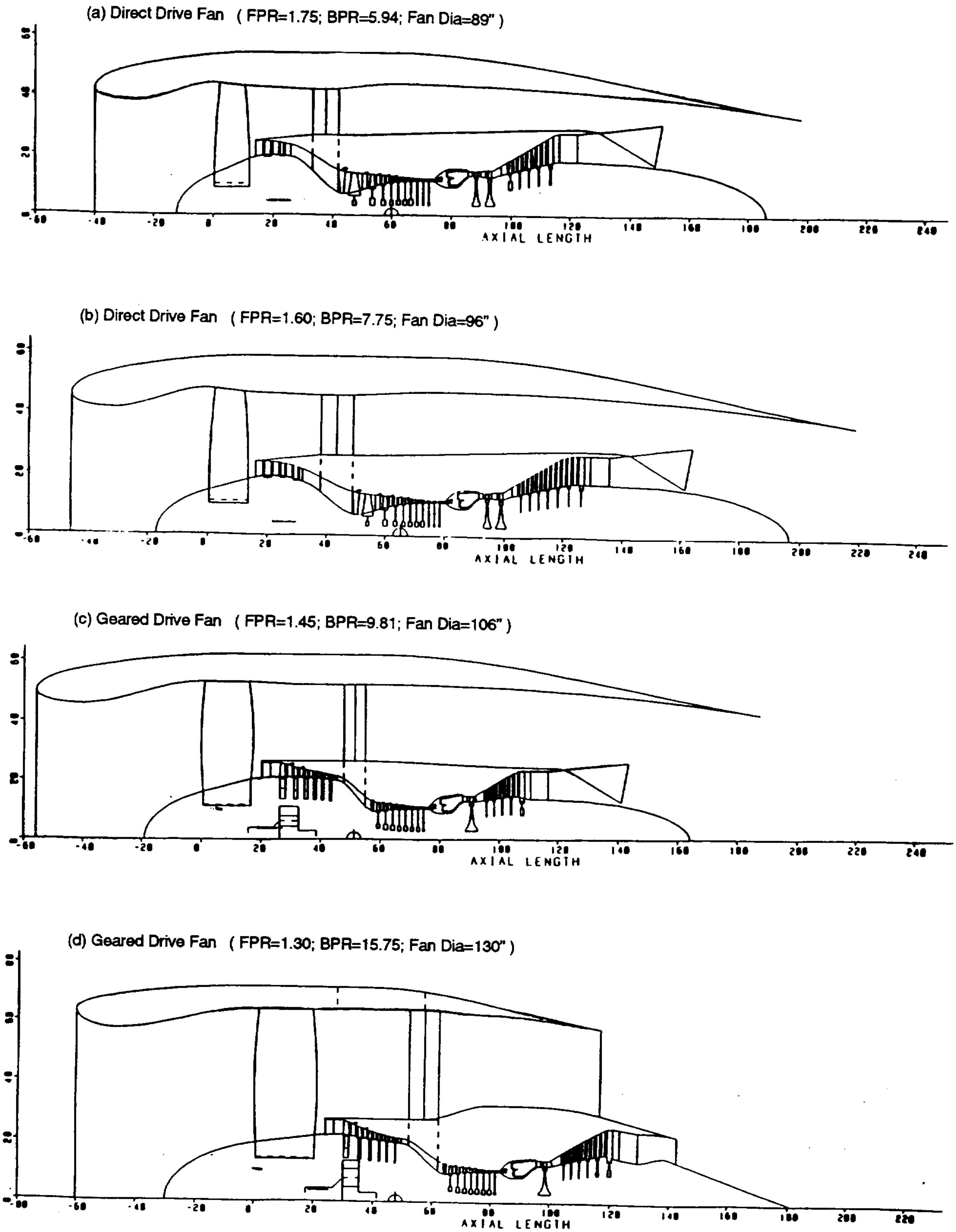


FIGURE 1 ADVANCED ENGINE CROSS SECTIONS

Table 1
UHB Study Engine Cycle and Geometry Parameters (Ref. 1)

	Study Engine Designation			
Parameter	**S75**	**S60**	**S45**	**S30**
Design FPR	1.75	1.60	1.45	1.30
Design BPR	5.94	7.75	9.81	15.75
Exhaust Type	Mixed	Mixed	Mixed	Separate
Fan Drive	Direct	Direct	Geared	Geared
Fan Diameter	89"	96"	106"	130"
Design Fan U_t	1480	1354	1030	984 (fps)
Sideline:				
Fan U_t	1496	1353	1038	947 (fps)
Fan PR	1.777	1.615	1.484	1.295
Takeoff:				
Fan U_t	1511	1364	1052	955 (fps)
Fan PR	1.790	1.625	1.496	1.300
Cutback:				
Fan U_t	1340	1222	932	859 (fps)
Fan PR1.579	1.465	1.365	1.24	
Approach:				
Fan U_t	935	850	653	566 (fps)
Fan PR	1.22	1.178	1.143	1.096

3.2 Preliminary Broadband Noise Mechanisms Identification and Assessment

A review of existing literature and data sources was carried out to identify candidate mechanisms for fan broadband noise generation. Analytical Services and Materials, Inc. (AS&M) was subcontracted to help in this effort. Mr. Stanley Lamkin of AS&M was the subcontractor principle investigator. Four principal mechanisms of fan broadband noise generation were identified for further evaluation and ranking:

1. Inlet boundary layer turbulence-rotor tip interaction
2. Inlet free-stream turbulence-rotor interaction
3. Rotor wake and vortex turbulence-stator interaction
4. Blade and vane surface boundary layer and trailing-edge turbulence flow noise

First-order estimates of various hypothesized mechanisms for fan broadband noise generation were carried out to quantifiy and rank the most important fan broadband noise mechanisms. These estimates were made using improvements and modifications to past theoretical models for blade/vane-turbulence interaction. For rotor-inflow turbulence, rotor-inlet boundary layer turbulence interaction, and stator-rotor wake turbulence interaction estimates, the models of references [7, 8] were modified and used in this study.

The empirical model of Mugridge [6] was used to estimate the broadband noise produced by the surface boundary layer turbulence and trailing edge turbulence fluctuations of rotor blades and stator vanes.

Data from five existing engines available from past GE test programs were collected and the fan broadband noise levels were extracted and correlated for the purpose of preliminary theory-data comparisons. Predictions were made of fan broadband noise using the above-described first-order models for the engine data sets collected and correlated. Results were compared quantitatively, and potential mechanisms and controlling parameters for broadband noise generation were deduced.

3.3 Follow-on Analytical Model Development and Experimental Program Plan

Based on the findings of the system impact study and the mechanisms identification subtasks, a plan for quantification of fan broadband source noise generation mechanisms and controlling parameters was developed. The plan includes experimental test program recommendations for diagnostic and validation tests, based on both scale model UPS rig and engine test vehicles. An analytical modeling plan to develop a validated prediction model code for fan broadband noise, integrated with the test program, was also developed.

4.0 SYSTEM STUDY RESULTS
Fan Broadband Noise Impact on UHB Engine System Noise

4.1 Fan Tone Contributions:

The four UHB engine designs studied in Reference [1] and summarized in table 1 were used as a basis for evaluating the contributions of broadband noise to overall system noise. The community noise levels in EPNdB were calculated for a typical large twin-engine airplane at each of four community noise certification points: (1) sideline, (2) takeoff with full power, (3) takeoff with cutback, and (4) approach. The engines were all sized to a 62,000 lb SLS thrust rating, and the aircraft selected had a 400,000 lb. takeoff gross weight. Fan blade-passing frequency tones and the next two harmonics were then edited out of the fan component spectra, and the flyover noise levels were recalculated.

Figure 2 shows the contribution of fan tones (BPF, 2BPF and 3BPF) to flyover noise levels for each of the four engines at four community noise measurement conditions. Because of the nature of the fan design selection process as a function of bypass ratio, fan tones are a more predominant contribution for fans operating at high pressure ratios (or lower bypass ratios). The tone contributions range from a high of 2 to 3 EPNdB in system noise at takeoff for a moderate bypass ratio engine, to a small fraction of a dB at approach for an ultra-high bypass engine. It is clear from figure 2 that reducing only fan tone noise will yield small benefits in engine system noise reduction. As engine design bypass ratio is increased, the benefit diminishes. Thus there is a strong motivation to evaluate fan broadband noise contributions and assess the benefits of reducing fan broadband noise.

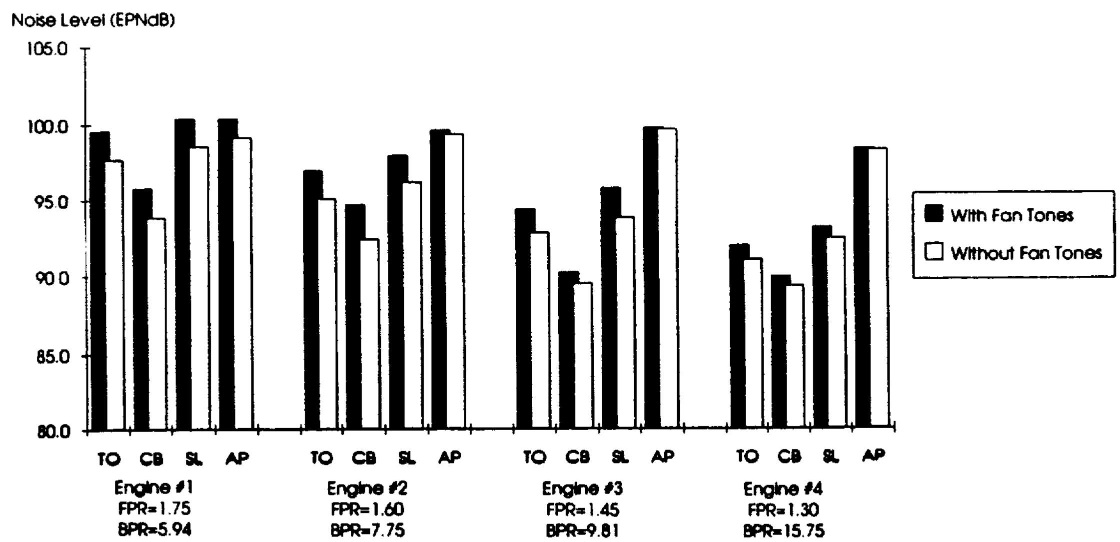


FIGURE 2 CONTRIBUTION OF FAN TONES (1,2,3 BPF) TO COMMUNITY NOISE LEVELS
(re: Figure 1 Baseline Engines)

4.2 Fan Broadband Level Contributions:

Broadband noise contributions to flyover noise levels of these four engines were further studied by applying reductions in four different steps(-1,-3,-5, and -10 dB) to the fan noise spectra, for three scenarios. The first case assumed that fan tones and broadband noise were equally reduced, by the above step amounts, such as might be achieved by adding more inlet and exhaust duct treatment. The second scenario assumed broadband noise reduction was achieved by source mechanism reduction, e.g., by fine scale turbulence reduction, and the fan tones remained unchanged. Again, four incremental steps of broadband noise reduction were used for parametric evaluation. The final scenario studied was to assume that all fan tones were eliminated such that fan broadband noise would be the only remaining component of the fan noise, again reduced in four incremental amounts.

Tables 2 and 3 show the results of these studies. Table 2 shows the predicted system absolute noise levels, while Table 3 shows the relative changes in system noise. A maximum system noise reduction 4.9 EPNdB was obtained for the extreme case of 10 dB broadband noise reduction and all fan tones eliminated. When both tones and broadband noise are reduced, the "average" effect is that the system noise reduction is about half the broadband noise reduction. When only broadband noise is reduced, the system noise reduction is considerably less. There are subtle effects of Bypass ratio (or engine type) and power setting, but no clear trends are observed from these results. Figure 3 shows the trends of system noise reduction from table 3 for the scenario where all fan tones are eliminated. These results (figure 3) give greater total system noise reductions at more modest broadband noise reduction levels than do the results when tone levels are reduced by the same amount as the broadband noise (scenario 1) or when the tone levels are left constant (scenario 2), as would be expected.

Table 2 Fan Broadband Noise Impact

TOTAL SYSTEM NOISE SUMMARY

Constant Fan BBN Reduction (dB)		applied equally to tones and broadband					applied only to broadband					without fan tones				
		0	1	3	5	10	0	1	3	5	10	0	1	3	5	10
Engine #1	Takeoff	99.6	99.1	98.3	97.7	96.5	99.6	99.5	99.3	99.3	99.4	97.7	97.5	97.1	96.8	96.3
FPR=1.75	Cutback	95.8	95.2	94.2	93.3	91.9	95.8	95.6	95.4	95.3	95.2	93.8	93.4	92.7	92.3	91.6
BPR=5.94	Sideline	100.4	99.9	99.0	98.4	97.4	100.4	100.3	100.1	100.1	100.2	98.6	98.3	97.9	97.6	97.1
	Approach	100.4	99.7	98.6	97.6	95.9	100.4	100.2	99.8	99.5	99.5	99.2	98.6	97.7	96.9	95.5
Engine #2	Takeoff	97.0	96.4	95.5	94.8	93.4	97.0	96.9	96.7	96.6	96.7	95.1	94.7	94.2	93.8	93.1
FPR=1.60	Cutback	94.7	94.0	92.7	91.7	90.0	94.7	94.4	94.1	93.9	93.8	92.4	91.8	90.9	90.2	89.2
BPR=7.75	Sideline	98.0	97.4	96.3	95.5	94.4	98.0	97.8	97.5	97.4	97.5	96.2	95.8	95.2	94.7	94.0
	Approach	99.7	99.2	98.0	97.1	95.4	99.7	99.3	98.5	98.0	97.3	99.4	98.9	97.8	97.0	95.4
Engine #3	Takeoff	94.4	93.8	92.8	92.2	90.6	94.4	94.2	93.8	93.7	93.8	92.8	92.4	91.7	91.2	90.3
FPR=1.45	Cutback	90.2	89.6	88.4	87.6	86.5	90.2	90.0	89.6	89.4	89.4	89.5	88.9	88.0	87.3	86.4
BPR=9.81	Sideline	95.8	95.1	94.0	93.2	91.7	95.8	95.6	95.2	95.1	95.1	93.8	93.3	92.6	92.1	91.1
	Approach	99.8	99.1	98.0	97.0	95.3	99.8	99.1	98.0	97.1	95.6	99.7	99.0	97.9	97.0	95.3
Engine #4	Takeoff	91.9	91.2	90.1	89.2	87.8	91.9	91.6	91.2	91.1	91.1	91.0	90.4	89.4	88.7	87.5
FPR=1.30	Cutback	89.9	89.2	87.9	86.9	85.5	89.9	89.4	88.5	87.9	87.3	89.3	88.6	87.5	86.6	85.3
BPR=15.75	Sideline	93.1	92.4	91.3	90.4	88.9	93.1	92.9	92.5	92.3	92.3	92.4	91.7	90.7	89.9	88.6
	Approach	98.4	97.8	96.8	96.1	95.0	98.4	97.9	96.9	96.3	95.3	98.3	97.7	96.8	96.1	N/A

Table 3 Fan Broadband Noise Impact

TOTAL SYSTEM NOISE DELTA SUMMARY

re: baseline with tones

Constant Fan BBN Reduction (dB)		applied equally to tones and broadband					applied only to broadband					without fan tones				
		0	1	3	5	10	0	1	3	5	10	0	1	3	5	10
Engine #1	Takeoff	99.6	0.5	1.3	1.9	3.1	0.0	0.1	0.3	0.3	0.2	1.9	2.1	2.5	2.8	3.3
FPR=1.75	Cutback	95.8	0.6	1.6	2.5	3.9	0.0	0.2	0.4	0.5	0.6	2.0	2.4	3.1	3.5	4.2
BPR=5.94	Sideline	100.4	0.5	1.4	2.0	3.0	0.0	0.1	0.3	0.3	0.2	1.8	2.1	2.5	2.8	3.3
	Approach	100.4	0.7	1.8	2.8	4.5	0.0	0.2	0.6	0.9	0.9	1.2	1.8	2.7	3.5	4.9
Engine #2	Takeoff	97.0	0.6	1.5	2.2	3.6	0.0	0.1	0.3	0.4	0.3	1.9	2.3	2.8	3.2	3.9
FPR=1.60	Cutback	94.7	0.7	2.0	3.0	4.7	0.0	0.3	0.6	0.8	0.9	2.3	2.9	3.8	4.5	5.5
BPR=7.75	Sideline	98.0	0.6	1.7	2.5	3.6	0.0	0.2	0.5	0.6	0.5	1.8	2.2	2.8	3.3	4.0
	Approach	99.7	0.5	1.7	2.6	4.3	0.0	0.4	1.2	1.7	2.4	0.3	0.8	1.9	2.7	4.3
Engine #3	Takeoff	94.4	0.6	1.6	2.2	3.8	0.0	0.2	0.6	0.7	0.6	1.6	2.0	2.7	3.2	4.1
FPR=1.45	Cutback	90.2	0.6	1.8	2.6	3.7	0.0	0.2	0.6	0.8	0.8	0.7	1.3	2.2	2.9	3.8
BPR=9.81	Sideline	95.8	0.7	1.8	2.6	4.1	0.0	0.2	0.6	0.7	0.7	2.0	2.5	3.2	3.7	4.7
	Approach	99.8	0.7	1.8	2.8	4.5	0.0	0.7	1.8	2.7	4.2	0.1	0.8	1.9	2.8	4.5
Engine #4	Takeoff	91.9	0.7	1.8	2.7	4.1	0.0	0.3	0.7	0.8	0.8	0.9	1.5	2.5	3.2	4.4
FPR=1.30	Cutback	89.9	0.7	2.0	3.0	4.4	0.0	0.5	1.4	2.0	2.6	0.6	1.3	2.4	3.3	4.6
BPR=15.75	Sideline	93.1	0.7	1.8	2.7	4.2	0.0	0.2	0.6	0.8	0.8	0.7	1.4	2.4	3.2	4.5
	Approach	98.4	0.6	1.6	2.3	3.4	0.0	0.5	1.5	2.1	3.1	0.1	0.7	1.6	2.3	3.4

4.3 System Benefit Summary:

If we assume that engine #1 is the "baseline" (BPR=6), representative of today's (1992) engine technology, then somewhere between 3 and 4 EPNdB can be realized by fan tone elimination and "reasonable" amounts of fan broadband noise reduction. This would fall far short of the previously-cited NASA goal of 7 to 10 EPNdB noise reduction for year-2005 technology. However, if a higher bypass ratio engine design is selected, then a total system noise reduction of 7 to 10 EPNdB can be achieved relative to this "baseline" engine (Table 2).

Needless to say, the fan tones need to be eliminated, reduced by design, or absorbed by additional treatment to achieve the above noise reductions. If fan tones are not alleviated, there would not be much benefit to reducing broadband noise level alone, since EPNL values for fans are dominated by the fan tones and their protrusion above the broadband levels. An additional EPNL penalty can actually result from only reducing broadband noise because of the tone protrusion penalty or 'tone correction' process in computing EPNL.

The inverse was also deduced, i.e., without broadband noise reduction, reducing fan tone noise only does not yield very significant system noise reductions (see figure 2). With a combination of engine cycle change (e.g., replacing Engine #1 with Engine #3 or Engine #4), a total system noise reduction of 7 to 10 EPNdB at aircraft departure conditions can be achieved, by reducing both fan tone and broadband noise levels, although the noise benefit at approach condition is still limited by the airframe noise level.

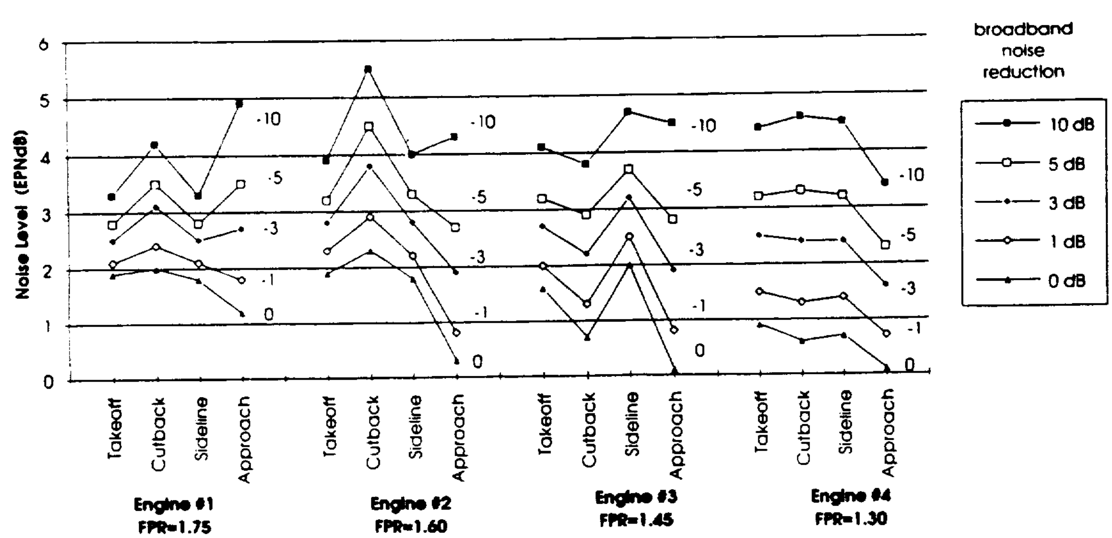


FIGURE 3 CONSTANT BROADBAND NOISE REDUCTION WITH FAN TONES ELIMINATED (re: Baseline Engines With Fan Tones)

5.0 LITERATURE SURVEY

5.1 Overview:

A literature survey was conducted using the database retrieval systems (Recon, Stilas, Dialog, etc.) available at the NASA Langley Research Center Technical Library. The search technique began with the development of key words and phrases. Literature groups were formed from basic words like "turbulence: and specific terms such as "rotor-stator." Boolean search methods were then used to find appropriate intersections. An optimum search pattern was developed using key words, locations (e.g., title, abstract), and specified authors. The goal was to find all appropriate references while minimizing the clutter of extraneous entries. Two surveys were conducted. The first survey looked for broadband noise models due to rotating blades, in order to obtain quantitative expressions for use in evaluating the important turbulence properties for source modeling. The second search then focused on ducted flow and turbomachinery turbulence literature in order to find qualitative and quantitative descriptions of the relevant turbulence characteristics. The literature search included the work done in Europe, Japan, Australia and the United States. The literature survey results, although quite extensive, revealed very little meaningful data in the area of turbulence measurements.

5.2 Broadband Noise Mechanisms:

There were several important earlier works on the generation of fan broadband noise published in the 1960's and 1970's.. Of particular interest were the fundamental investigations on turbulence/blade interactions by Sharland, reference [5], who carried out experimental measurements of the various components of turbulence noise from isolated flat plates, and derived quantitative expressions for vortex shedding noise, noise from turbulence, and surface boundary layer radiation. Sharland also carried out some interesting fundamental experiments on small, low-speed fans which illustrated the relative contributions of the various proposed noise mechanisms, and showed reasonable agreement with simple models of these mechanisms. Blade-turbulence interaction was studied analytically by Morfey [3], Mugridge [6], and Mani [7,8].

More recent analytical work by Kerschen and Gliebe [16,17] extended the previous turbulence-blade interaction noise theory to blade interactions with non-isotropic turbulence. Glegg [22] has developed a theory for predicting fan forward-radiated broadband noise, relating it to inlet length and corresponding impact on endwall boundary layer turbulence. Glegg [22,23] also developed a corresponding theory for aft-radiated broadband noise with dependence on blade loading and corresponding blade wake/boundary layer momentum thickness. Glegg [24] also carried out an extensive evaluation of his theories [22, 23] with data obtained by Woodward et al [25] from tests of an ultra-high bypass advanced ducted propeller (ADP) scale model fan.

Empirical correlations of scale model fan and engine rig test acoustic data, relating fan broadband noise to fan blade incidence angle were proposed and developed by Smith and House [20], Benzakein et al [18], Burdsall and Urban [19], Wright [15], Ginder and Newby [10], and Gliebe [11].

The experimental measurements reported by Mugridge and Morfey [26] showed that fan rotor tip clearance has an effect on fan broadband noise, presumeably because of the secondary flows associated with tip clearance and the corresponding turbulence changes with changes in tip clearance. Their study showed that the noise level first decreased with increasing tip clearance, then increased with further increases in tip clearance. The implication is that the ratio of endwall boundary layer thickness to tip clearance may be an important parameter governing the broadband noise produced by inlet boundary layer turbulence-rotor tip interaction. Goldstein et al [27] demonstrated a substantial reduction of broadband noise of a turbofan engine could be achieved by bleeding off the inlet duct wall boundary layer. The broadband level and the amount of reduction was found to be sensitive to the fan loading, which was changed by reducing fan nozzle area.

An alternative approach to fan broadband (and tone) noise modeling was developed by Hanson [9, 28, 29], for fans with "short" ducts, i.e., using a free-space radiation model of rotating and stationary point sources. Hanson proposed a "Pulse-Position Modulation" (PPM) and "Pulse-Amplitude Modulation" (PAM) approach for simulating the tone and broadband noise generation. The modulation of the periodic gusts impinging on rotor blades and stator vanes was described in terms of statistical variations of gust amplitudes and periodicity. Hanson was reasonably successful in explaining many features of low-speed ducted fans, especially the nature of fan noise caused by ingestion of atmospheric turbulence during ground tests. His work emphasized the importance of the non-homogeneous, anisotropic features of ingested turbulence in explaining the observed fan spectral features.

5.3 Isolated Airfoil Broadband Noise Studies:

Experimental and theoretical work on the self noise generated by airfoils in a stream have been reported by Mugridge [30], Clark [31], and Brooke [32]. More recent experimental airfoil and fan broadband noise work was published by George and Chou [12], and Akishita & Ohtsuta [21]. Although it can be argued that the broadband noise produced by isolated airfoils does not contain all the mechanisms present in an actual fan stage, there are similar mechanisms that can be studied using isolated airfoil experiments, e.g., inflow turbulence-airfoil interaction. Also, the understanding of isolated airfoil noise generation physics can lead to ideas for identifying fan stage noise generation mechanisms. It can further be argued that estimating fan stage broadband noise using isolated airfoil noise characteristics provides a noise "floor" that represents the minimum broadband noise produced by a fan stage. An excellent analytical treatment of the broadband noise generated by an airfoil in an incident turbulent flow was presented by Goldstein [33], which could serve as a baseline approach for further analytical development of the theory of broadband noise of airfoils in cascades and in rotating blade rows. Fathy and Rashed [34] published a similarly detailed analytical development for isolated airfoil vortex-shedding noise. Again, this could serve as a basis for further analytical studies of cascade and rotating blade row broadband noise.

5.4 Low Tip Speed Fan Studies:

Some interesting theoretical modeling of fan broadband noise for application to cooling fans , ventilating fans and exhaust fans was carried out by Fukano et al [35], and attempts were made to verify the modeling approach with experimental measurements by Fukano et al [36]. Simple formulae were developed from the theoretical models of Sharland [5], and good agreement with fan experimental test results were obtained when measured wake widths were input to the formulae. In [36], the effects of blade number, chord length and blade camber were investigated experimentally, and the theoretically-derived simple formulae of [35] were shown to agree with the experimental trends. A correlation was demonstrated between the ratio of blade wake width-to blade spacing ratio and broadband sound power level.

Longhouse [37] investigated the vortex-shedding noise of low-speed fans experimentally, including the influence of serrated leading edges. Substantial reductions in high-frequency broadband noise were observed with the leading edge serrations, and that the amount of reduction decreases as the fan is throttled toward the stall point. The noise generation mechanism identified in these experiments (vortex-shedding) was attributed to instabilities in the laminar boundary layer on the suction side of the blades, i.e., Tollmien-Shchlichting waves, and the interaction of these waves with the blade trailing edge in some sort of feedback mode. These results suggest that devices such as leading edge serrations may provide significant broadband noise reduction for an aircraft engine fan, as long as the blade (or vane) loading is not too high.

5.5 Turbulent Wakes:

Turbulence in the wakes shed by fan rotor and stator airfoils is an important source of broadband noise. The turbulent fluctuations can produce sound radiation, and the turbulence from an upstream blade row can impinge upon a downstream blade row, producing random lift fluctuations on the downstream row, and again generating random sound. Hansen and Okiishi [38] experimentally studied the effects of a rotor wake on stator surface boundary layers. They used surface-mounted hot-film shear gages to sense the rotor wake effects at several chord-wise locations, up to 85% chord at the mid-span location. Their measurements show that the laminar boundary layer on the forward portion of the stator blade becomes turbulent in the presence of the rotor wake segments. The rotor wake segment effect (intermittency?) became larger further downstream and moved along the stator surface as turbulence would move (convection).

Lakshminarayana and Reynolds [39] measured the turbulence intensities in the near wake of a compressor blade. Their hot-wire measurements showed that the turbulence intensities decay very rapidly in the near wake region. They found the radial component of turbulence intensity to be much higher than the tangential and axial components. Matsuuchi and Adachi [40] experimentally studied the wake of an upstream stator and the corresponding three-dimensional structure of the flow in a downstream rotor passage, using a hot-wire anemometer. Their results indicated that the stator wake becomes deeper as it goes closer to the pressure surface of the rotor blade. Shaw and Balombin [41] measured turbulent wake properties at three axial locations behind a fan rotor using a cross-film anemometer. The also measured the effect of fan speed and inflow turbulence on the wake properties. Their results indicated that the maximum wake turbulence intensity increases in the tip and hub regions with increasing fan speed. Measurements of rotating blade surface boundary layer turbulence by Lakshminarayana et al [42] showed maximum turbulence intensities of 16% close to the surface and about 8% in the free stream. Walker [43] measured the development of turbulent boundary layer on an outlet guide vane of a single-stage compressor, obtaining results similar to that of [42] for rotor blades.

Lakshminarayana and Davino [44] experimentally studied stator and inlet guide vane wakes using single- and cross-wire anemometers. Their measurements covered several spanwise locations, near the trailing edges and far downstream (two chord lengths). Very high turbulence intensities, on the order of 30 - 35%, were measured on the wake centerline. Spectral measurements were also made.

Glegg [22] proposed a model for rotor wake turbulence based on the Von Karman energy spectrum for free turbulence and turbulence scales related to wake momentum thickness, which can be related to the rotor profile drag coefficient. This model is claimed to also include the "intermittency" effect, i.e., the effect of the stator vanes "seeing" alternating smooth and turbulent regions corresponding to free-stream and wake regions as the rotor blades pass by. This model is a possible improvement to the turbulence model used by Mani [7] for stator-generated broadband noise, and should be pursued further, with experimental verification tests.

5.6 Casing/Annulus Wall Turbulence:

A very comprehensive measurement of the turbulence in the annulus wall region of a low-speed compressor stage was carried out by Davino [45]. His measurements indicate that the flow near the tip region is extremely complex due to the interaction of the free stream flow, secondary flow, tip leakage flow, blade boundary layer and/or wake. These measurements were carried out within the rotor blade passage and behind the rotor, and so they do not represent the end wall boundary layer turbulence *upstream* of the rotor. In fact, most of the identified literature containing information on end-wall boundary layer properties dealt with the influence of rotor tip clearance and secondary flows on the end-wall flow structure [26,45,46], and little quantitative information was uncovered on the boundary layer turbulence properties upstream of the rotor. This is an area where experimental measurements are sorely needed.

Glegg [22] utilizes a Von Karman type of turbulence energy spectrum for modeling end wall boundary layer turbulence, which incorporates an energy wave number k_e and dissipation wave number k_d, both of which are related to boundary layer thickness. The flat plate approximation for turbulent wall boundary layer thickness is used, and hence the rotor turbulence properties are defined. Again, experimental measurements would be useful in evaluating Glegg's model.

A summary review and empirical correlation of much of the above-cited wake and endwall turbulence information was carried out by Majjigi and Gliebe [47]. This work included correlations of wake mean velocity profile deficit decay and wake width spreading, as well as turbulence intensity decay correlations and turbulence intensity profile correlations.

6.0 FAN BROADBAND NOISE ENGINE DATA TRENDS

A procedure was described by Gliebe[11] for extracting and correlating the fan broadband noise from fan scale model test data. It was felt useful to attempt the same procedure using actual turbofan engine acoustic test data. Five sets of GE engine acoustic data were processed to extract fan broadband noise from the actual engine measured spectra. Table 2 lists some of the geometric parameters for these five engines. They cover the range from fan design tip speeds of approximately 1200 to 1450 ft/sec, and fan design pressure ratios of 1.5 to 1.75.

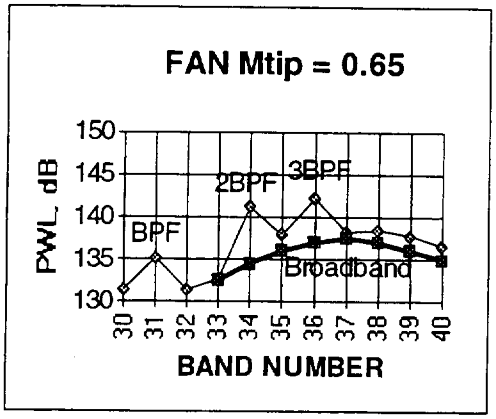
Table 2
Data Base Engine Geometric Parameters

ENGINE NO.	FAN BLADE NO.	OGV / STATOR NO.	BLADETIP METAL ANGLE	HUB / TIP RADIUS RATIO	TIP ROTOR CHORD (INCHES)	TIP R - S SPACING S/C	PITCH ROTOR CHORD (INCHES)	PITCH R - S SPACING S/C	HUB ROTOR CHORD (INCHES)	HUB R - S SPACING S/C
1	38	80	64.6	0.37	9.15	1.27	7.23	1.02	5.86	0.31
2	38	80	62.4	0.37	9.15	1.26	7.23	1.57	5.97	0.28
3	38	80	63.7	0.36	9.37	1.41	7.36	1.19	6.37	0.21
4	32	34	61.6	0.35	11.30	2.00	9.00	1.91	7.40	0.26
5	28	60	65.9	0.42	12.54	0.68	7.96	0.55	N/A	N/A

All fan dimensions were scaled to a common fan diameter of 83.0 inches

The measured acoustic data were normalized to an 83-inch fan diameter to scale all data to a common size for correlations. Sound power levels were calculated based on measurements taken from farfield microphones in an outdoor test arena over a concrete surface. For certain data sets, at higher power settings, the fan broadband noise overlaps significantly with the exhaust jet mixing noise and combustor core noise at very low frequencies. The extraction process therefore has significant uncertainty when this is so.

In addition, fan broadband noise levels derived from the measured engine data were inferred by the process of smoothing the one-third octave spectra after reducing the 1/3-octave bands which contained the fan Blade-Passing Frequency (BPF) tone and the next two harmonics to the average of the adjacent higher and lower bands. This process is illustrated in figure 4. A more effective method would have been to extract the fan tones from narrow-band spectra, and subtract the narrow-band tone (1,2, and 3XBPF) levels from the appropriate 1/3-octave band levels, leaving the "broadband" noise remaining. Unfortunately, narrow-band data were not available for some of the selected engine test data, so the less certain procedure described above (smoothing) was used, and the process was consistently the same for all engine data sets. One engine set was evaluated both ways (1/3-octave editing and smoothing vs. narrowband tone subtraction), and the difference was found to be small, on the order of 1 dB or less. Figure 5 shows a sample typical of the results obtained which compares the two methods of extracting the fan broadband noise from the engine spectra.



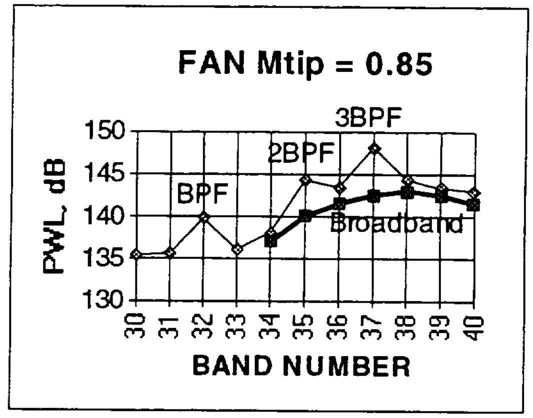
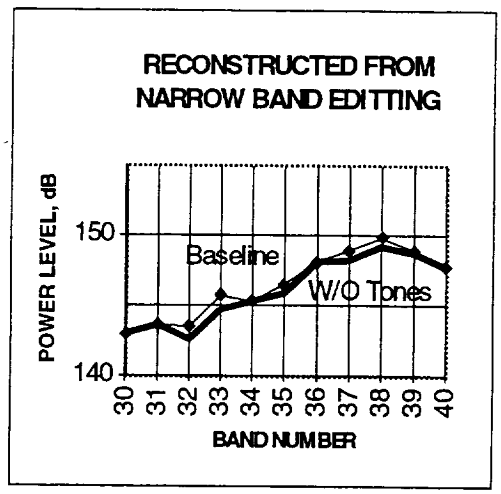
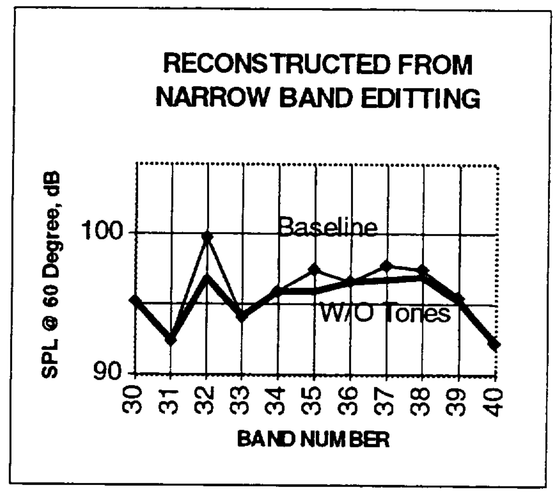


FIGURE 4 COMPARISON OF INFERRED FAN BROADBAND NOISE SPECTRA WITH MEASURED ENGINE NOISE SPECTRA



Baseline OAPWL=159.5
N/B Edited OAPWL=159.3



Baseline OASPL=94.5
N/B Edited OASPL=94.1

FIGURE 5 COMPARISON OF FAN BROADBAND NOISE SPECTRA DETERMINED BY USING ALTERNATIVE METHOD

Following the procedure outlined in reference [11], the peak (Overall?) broadband acoustic power levels were calulated from the "broadband" SPL spectra, and then the resulting levels, scaled to a common size as discussed above, were then correlated against fan tip relative Mach Number (or corrected tip speed?) and fan blade tip incidence angle. A multiple-regression analysis was employed to derive the correlation and corresponding coeffients.

Figure 6 shows the resulting correlation of the measured (extracted) data versus the correlation equation curve fit of broadband noise power level as a function of fan corrected tip speed for all five engines. The incidence angle effect, based on the derived correlation sensitivity of an increase in peak fan broadband PWL with incidence angle of 0.953 dB per degree, was removed from the measured points to show only the tip speed effect scatter. The correlation of measured data versus the derived correlation equation curve fit of broadband noise as a function of fan tip incidence angle is shown in figure 7. For this comparison, the tip speed effect, found to be roughly tip speed to the 5.5-power, was removed from the measured (extracted) data to show only the incidence effect data scatter. Further discussion of the broadband PWL spectral characteristics is postponed to the next section, when comparisons with analytical predictions are made.

These results are consistent with the results of reference [11] for the tip speed effect, although Tip Relative Mach Number, rather than corrected Tip Speed, was used in reference [11]. On the other hand, the sensitivity to incidence angle was found to be significantly lower for the engine data in the present study (0.95 dB/degree), compared to the scale model data result of 2.2 db/degree found in reference [11]. This could perhaps be due to the greater difficulty in extracting the true broadband noise from actual engine data due to the existence of other contributing sources, the cleaner, more controlled test environment and setup of the scale model tests[11], or it may indicate a scaling effect related to Reynolds Number that causes the scale model simulation of full scale engine fans to be more sensitive to incidence angle and therefore blade loading.

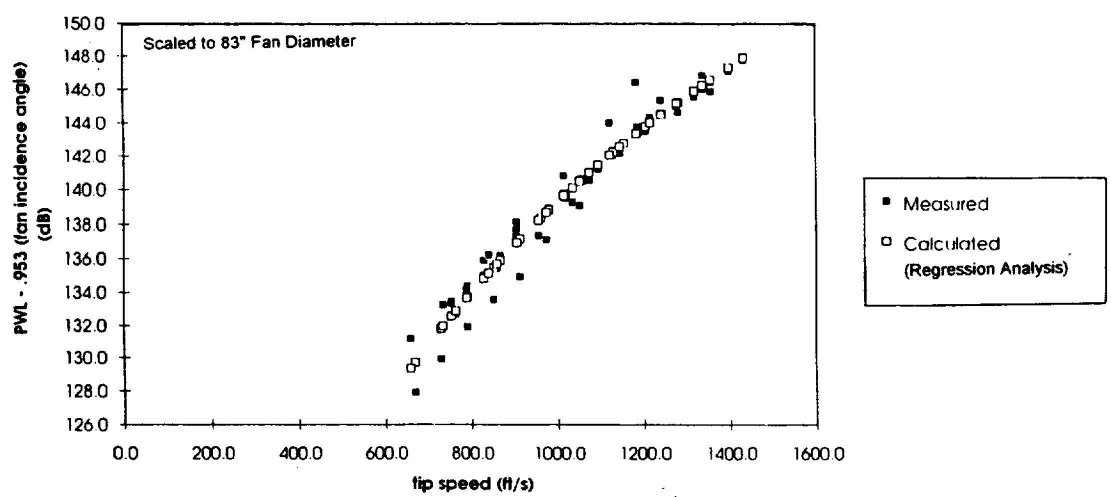


FIGURE 6 COMPARISON OF MEASURED AND CALCULATED FAN BROADBAND NOISE POWER LEVELS, WITH INCIDENCE ANGLE EFFECTS REMOVED

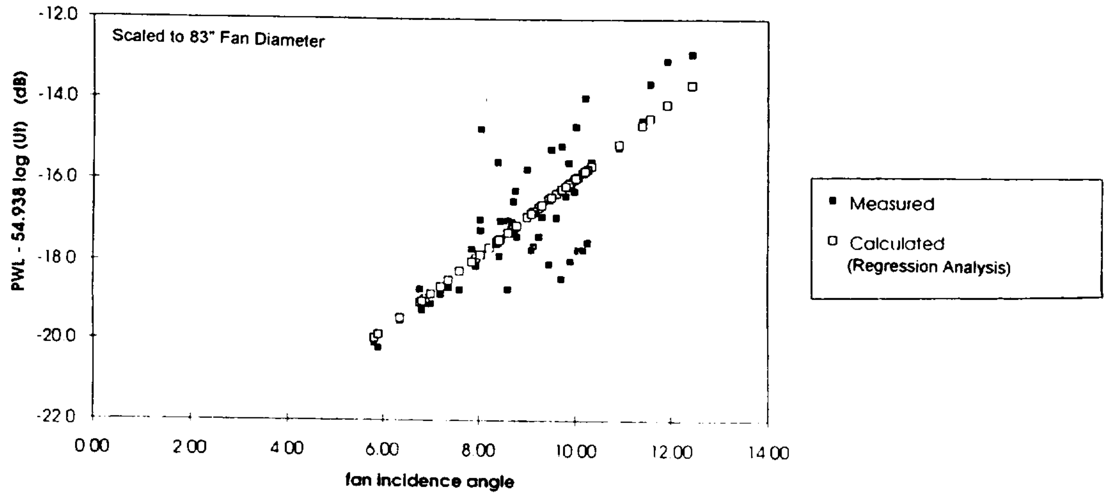


FIGURE 7 COMPARISON OF MEASURED AND CALCULATED FAN BROADBAND NOISE POWER LEVELS, WITH TIP SPEED EFFECTS REMOVED

7.0 FAN BROADBAND NOISE MECHANISMS ASSESSMENT

7.1 Analytical Model Selection and Approach:

As dicussed in section 5, a rather detailed model of the broadband noise generated by the interaction of inflow turbulence with a fan rotor was previously developed [7,8,16,17], and it has the capability to model some of the mechanisms of fan broadband noise thought to be important. Sharland [5] identified many of these mechanisms in his landmark article, and it was felt appropriate to apply the above analytical model to assessing the relative importance of these hypothesized mechanisms, using the latest available information on turbulence properties in fan stages. In fact, a primary objective of the literature survey described in section 5 was to find the best available information on turbulence levels, scales, etc., so that an update of Sharland's ordering analysis could be made, using the newer analytical models (not available when Sharland conducted his investigation), rather than using similarity arguments.

The primary mechanisms of broadband noise generation considered in this study are two proposed by Sharland [5]: (i) noise due to interaction of ingested free stream turbulence with either a rotor or a stator blade row; and (ii) noise due to turbulent boundary layers developed on blade and vane surfaces. Sharland [5] also proposed a third mechanism; namely, turbulent vortex shedding, but in the period of this study, a satisfactory *quantitative* evaluation of this mechanism was not feasible.

In the case of the turbulence–blade row interaction mechanism, we have relied heavily on prior GE work [7,8,16] and in particular [8]. The theory and computer programs developed in [8] are the ones used in the current first-order assessment study predictions. Although the theory and codes of [8] include both steady, circumferentially varying inlet distortion-induced noise generation and ingested inlet turbulence-induced noise generation, only the inlet turbulence-related analysis of [8] was used herein.

The theoretical model developed in [8] treats a two-dimensional cascade of staggered flat-plate airfoils with axial inflow of steady, uniform Mach number M_a, rotating in the tangential (y) coordinate direction at blade speed Mach number M_t. An isotropic, homogeneous model of ingested turbulence is assumed. The fluctuating lift forces produced by the ingested inflow turbulence are treated as point dipole sources moving at blade speed M_t and radiating into a uniform medium having flow Mach number M_a. The effects of blade loading are modeled by assuming a small incidence angle at the leading edge, and the interactive effect of the steady, leading-edge blade-to-blade flow variations with the turbulent velocity field is treated as a distribution of rotating quadrupole sources around the blades. The dipole (unsteady lift fluctuation) source mechanism is independent of blade loading, while the quadrupole (steady loading-turbulence interaction) sources, although acoustically less efficient than the dipole sources, are a strong function of loading. The two source types also have different dependencies on Mach number. The dipole mechanism is described in detail in [7], and the quadrupole mechansim is summarized in [8], along with a computer code listing which contains both mechanisms.

The rotor inlet boundary layer turbulence-rotor tip interaction mechanism can therefore be estimated with the above model, once the inlet boundary layer turbulence properties have been identified. The values of intensity and length scale for typical inlet duct wall boundary layers has been deduced based on the literature survey results discussed in section 5.

As noted in [7], the case of interaction with a stator can be obtained rather simply from the case of a rotor by setting the rotor tangential speed to zero. The case of turbulence-stator interaction noise arising from interaction of turbulence contained in the wake of the preceding rotor was therefore evaluated as a separate mechanism, and the assumptions used to quantify this mechanism are summarized in the following paragraphs.

Turbulence in the wakes of the rotor blades is assumed to be uncorrelated from blade–to–blade. The needed properties of the wake turbulence (intensity, scale, spatial extent) were correlated in terms of the upstream rotor blade row chord (c) and drag coefficient (C_D), similar to the past correlations for wake steady flow properties such as wake width and centerline velocity deficit, e.g., Hinze[48], Townsend[49], and Kemp and Sears[50]. Both Figure 6–5 of [48] and Figure 7–7 of [49] show that wake turbulence may be considered homogeneous (albeit of limited spatial extent) and isotropic. Based on the velocity defect at the wake centerline, the root-mean-square value of a single component of turbulent velocity may be taken (from both Figure 6–5 of [48] and Figure 7–7 of [49]) as approximately $\sqrt{0.08}$ or 28%. The transverse wake velocity defect (u), relative to the free-stream velocity (U), is assumed to have the form [48]:

$$\frac{u}{U}=\frac{C_D c}{2\sqrt{\ell\pi(x+a)}}\exp\left[\frac{-y^2}{(x+a)\ell}\right]$$

where (x,y) are chordwise and perpendicular to chord coordinates. Per [50], if x is measured from the mid-chord point, then a = -0.35c and by equations (10,12) of [50], we can deduce that:

$$\ell = c(0.68)^2 C_D / \pi$$

The quantity labeled Y in [50] is $\sqrt{\pi\ell(x+a)}$. Now Figures 6–3 of [48] suggest that the width of the wake over which significant turbulent intensities occur is about 1.643 times the wake half-width (defined as the width at which the wake defect is one half the centerline value). The wake half-width, from [50] is 0.47Y, and hence we take the "significant" wake width as 0.722Y, subject to the constraint, of course, that this width cannot exceed the normal gap between two adjacent blades. Finally, from Figure (7–9) of [49] and Figure 6–3 of [48], we can deduce that the longitudinal integral length-scale of the wake turbulence is about 94% of the wake half width.

Given the rotor stator axial spacing, and evaluating the wake properties at the mid chord location of the stator, all needed turbulence properties for evaluation of rotor wake turbulence–stator interaction noise can now be deduced in terms of the rotor drag coefficient. It may be noted that a disturbance convecting with the fluid in a coordinate system fixed with the rotor is also a disturbance convecting with the fluid in any other coordinate system, such as the one fixed to the stator. If the rotor wake turbulence is anisotropic (not assumed in the present study), then of course a coordinate system aligned with and normal to the rotor wake may be the most convenient to describe length scales and intensities of turbulence. It may be noted from Figure 7–9 of [49] that the longitudinal length scales are roughly twice the transverse length scales, which is not true for homogeneous, isotropic turbulence.

With regard to turbulent boundary layer noise, the formulae given in [6] were adopted without modification. According to [6], with U, c, C_D denoting the flow relative velocity, chord and drag coefficient, a frequency f_0 is defined as:

$$f_o = U / (2DcC_D)$$

For frequencies "$f_0 < f < 2 f_0$", the third octave sound power is given by

$$W = 8 \bullet 10^{-6} \rho_o U^3 M_{rel}^3 NbcC_D$$

where ρ_o, M_{rel}, N, b denote the density, relative Mach number, number of blades, blade span. For "$2f_0 < f < 4 f_0$", sound power falls off at 3 dB per octave. For "$f > 4 f_0$" the fall off is at 8 dB per octave and for "f < f_0" the fall off is at 3 dB per octave. Mugridge [6] also gives a correction to the above formula for tip clearance effects, which is an adjustment to C_D based on fan rotor hub/tip ratio, clearance/span ratio, and tip solidity (chord/spacing). This correction was not used in this study, but it suggests an approach to modeling tip clearance effects which warrants further investigation. It should also be noted that, although the above formulae are labeled as predictions of "turbulent boundary layer noise" in reference [6], reference is made to trailing edge effects, and it is not clear that these formulae do not contain some effects of vortex-shedding, especially since they are empirically calibrated using model experiments (flat plates immersed in a flow) which could contain both mechanisms.

7.2 Mechanisms Assessment Study Results:

Using the above-described theoretical and empirical models for the various hypothesized fan broadband noise generation mechanisms, predictions were carried out for the five engines summarized in table 2 and discussed in Section (6). Predictions were made of broadband sound power spectra at several fan speeds, and these results are summarized in figures 8 through 12.

In case of the free stream turbulence-blade row interaction (rotors or outlet guide vane row) mechanisms, the following properties were assumed for the free stream turbulence (taken as homogeneous and isotropic) impinging on the blade rows:

(i.) Turbulence intensity, i.e. root-mean-square value of a component of turbulent velocity normalized by the freestream velocity (which is assumed to be an axial flow) is assumed to be 1.5%.

(ii.) Since the turbulence that we have in mind is that associated with the fine scale turbulence in the casing boundary layers, with L denoting the longitudinal integral length scale of the turbulence and D denoting the transverse pitch of the blades (at the tip), engine 1 is assumed to have the ratio L/D=0.1. If engine 1 has B_1 rotor blades and another engine has "B" rotor blades the value of L/D for the second engine is taken as (0.1) (B/B_1). This corresponds to taking L proportional to engine diameter which in turn is motivated by the idea that since we are dealing with engines whose inlet length/inlet diameter ratio is roughly the same, L proportional to inlet length (which seems reasonable) implies that L is proportional to engine diameter.

(iii.) The lift coefficient for quadrupole noise [8] is calculated based on incidence angle. In general, aerodynamic data such as incidence angles are not available at exactly the same speeds as the acoustic data, and were deduced by interpolation (as needed).

(iv.) The predictions were made only for the "strip" in the tip region, ascribing the annulus area associated with the outer 5% of the blade span to this tip "strip".

(v.) For both turbulence-rotor and turbulence-stator interactions, the drag coefficients for both rotor and stator blade rows were assumed to be equal to 0.015.

A final point concerning the acoustic data in Figures 8-12 is that the PWL data (inlet + exhaust) is obtained from the full data by "subtracting" out the tone noise in a somewhat subjective fashion, as discussed in Section (6) and illustrated in figures 4 and 5. The data in Figures 8-12 is given in terms of one-third octave PWL vs. octave band number (OBN). It may be recalled that the relation between center frequency "f_c" and OBN is: $f_c=10^{(OBN/10)}$, in Hz.

Figures 8a, 9a, 10a, 11a and 12a show side-by-side comparisons of predicted and measured (or rather, spectra deduced from measurements) spectra for the three turbulence interaction-related mechanisms (inlet turbulence–rotor interaction, inlet turbulence–stator interaction, and rotor-wake turbulence-stator interaction). Similarly, figures 8b, 9b, 10b, 11b, and 12b show a comparison of the measurements with the Mugridge formula [6] for turbulent boundary layer noise. The curves labeled as "data" in Figures 8a and 8b are the same, and similarly the "data" in 9a and 9b are the same, etc. Since the theory for quadrupole noise of [8] is restricted to subsonic relative Mach numbers, we were unable to carry out predictions for the data in Figures 8-12 where the rotor relative Mach number exceeded unity.

The data and predictions for Engine 1 (figure 8) show that the predicted broadband noise spectra for the turbulence-blade row interaction sources have about the right levels relative to the "data", but that the spectral shape is not duplicated well. The predicted spectra do not have the high-frequency roll-off exhibited by the data. There appears to be more predicted sensitivity to fan speed than suggested by the data.. The boundary layer turbulence spectra predicted by the Mugridge model appear to be significantly lower than the "data", by about 10 dB. Similar trends were obtained for the other engine data sets as well.

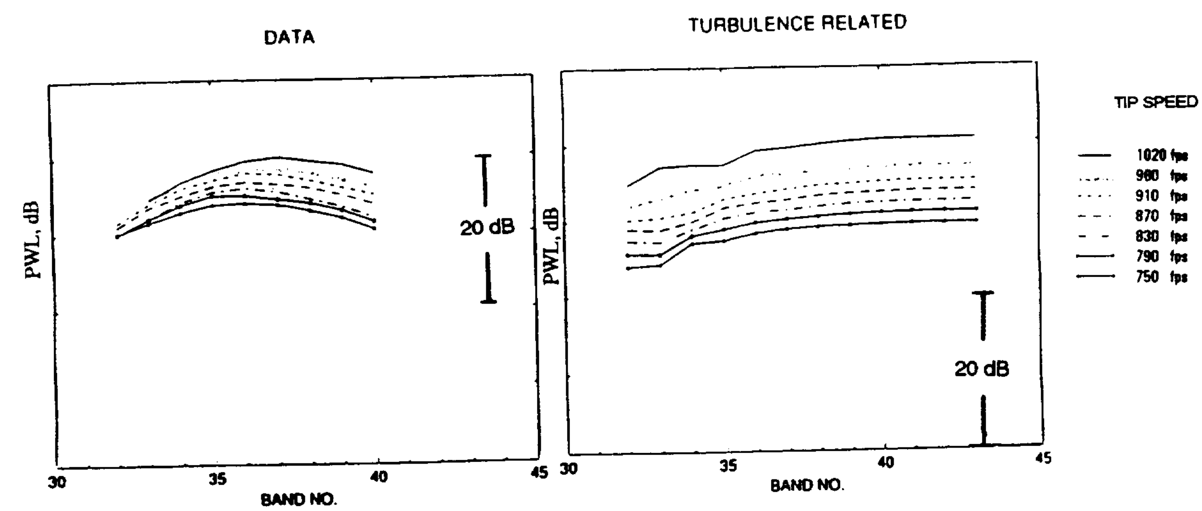


Figure 8a Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise from all the turbulence related mechanisms: Engine 1

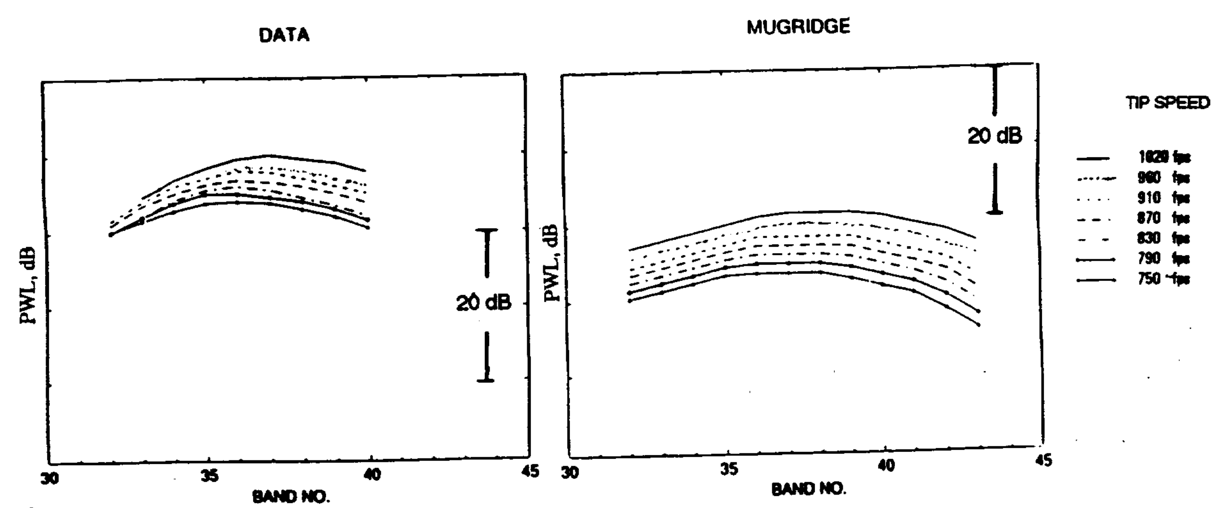


Figure 8b Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise (from rotor and stator) from turbulent boundary layer noise formulae of [8]: Engine 1

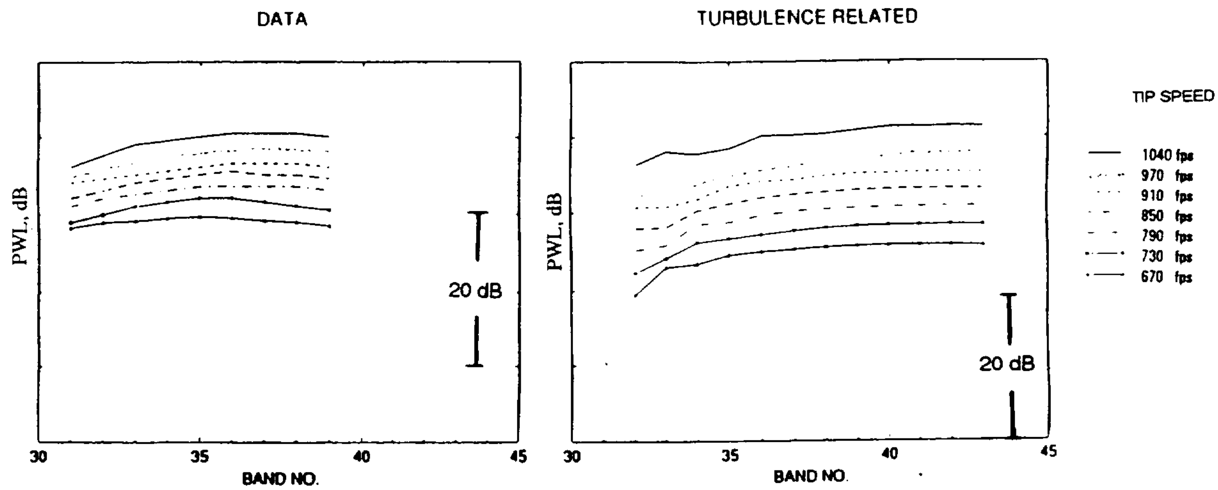


Figure 9a Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise from all the turbulence related mechanisms: Engine 2

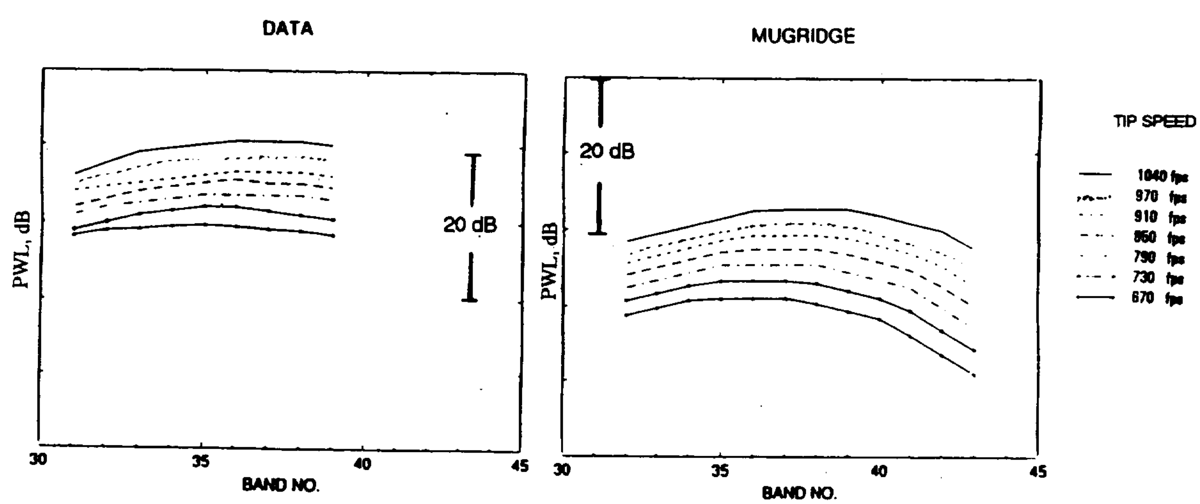


Figure 9b Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise (from rotor and stator) from turbulent boundary layer noise formulae of [8]: Engine 2

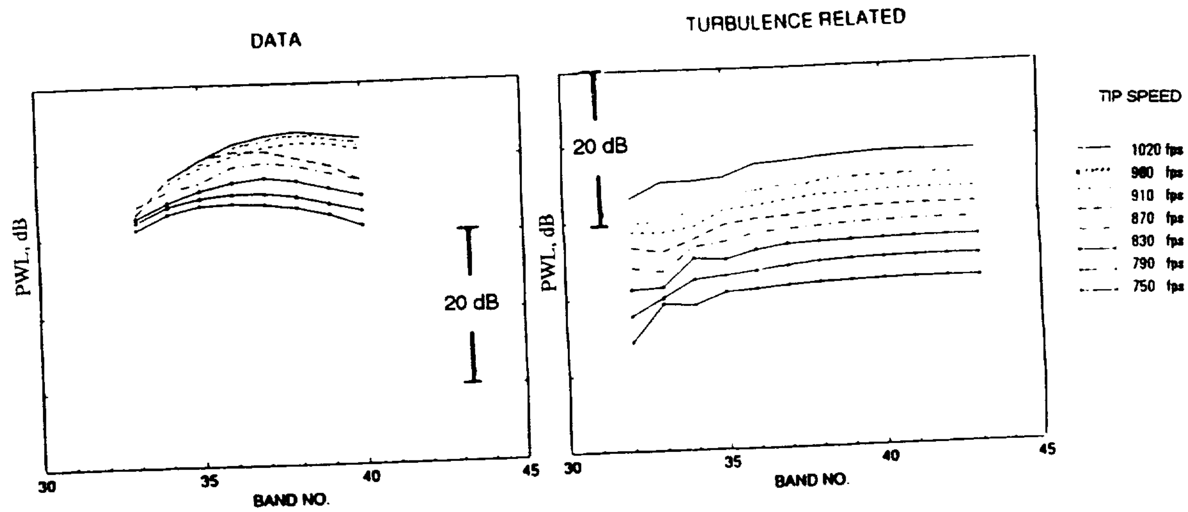


Figure 10a Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise from all the turbulence related mechanisms: Engine 3

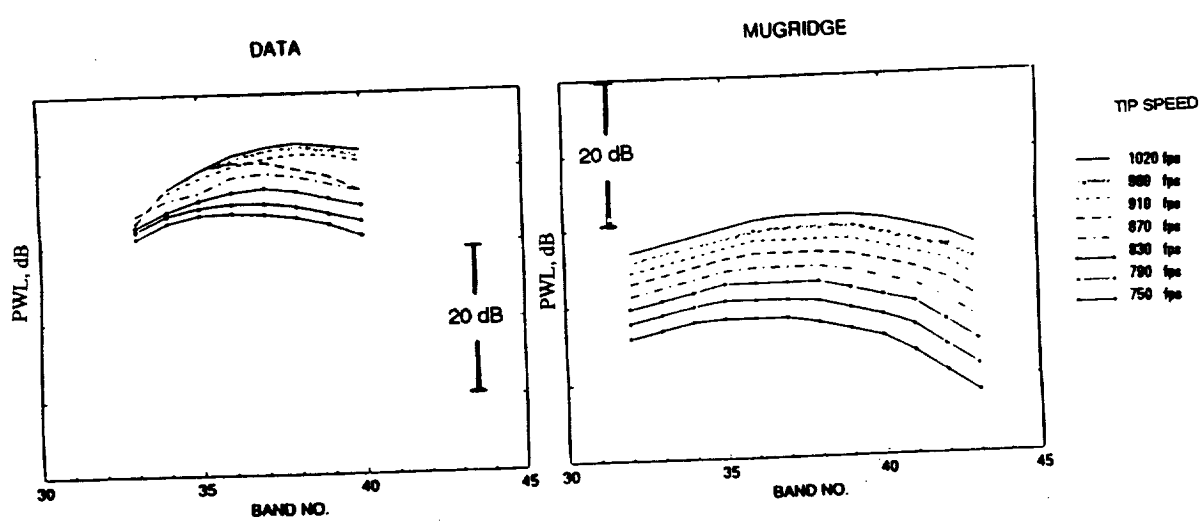


Figure 10b Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise (from rotor and stator) from turbulent boundary layer noise formulae of [8]: Engine 3

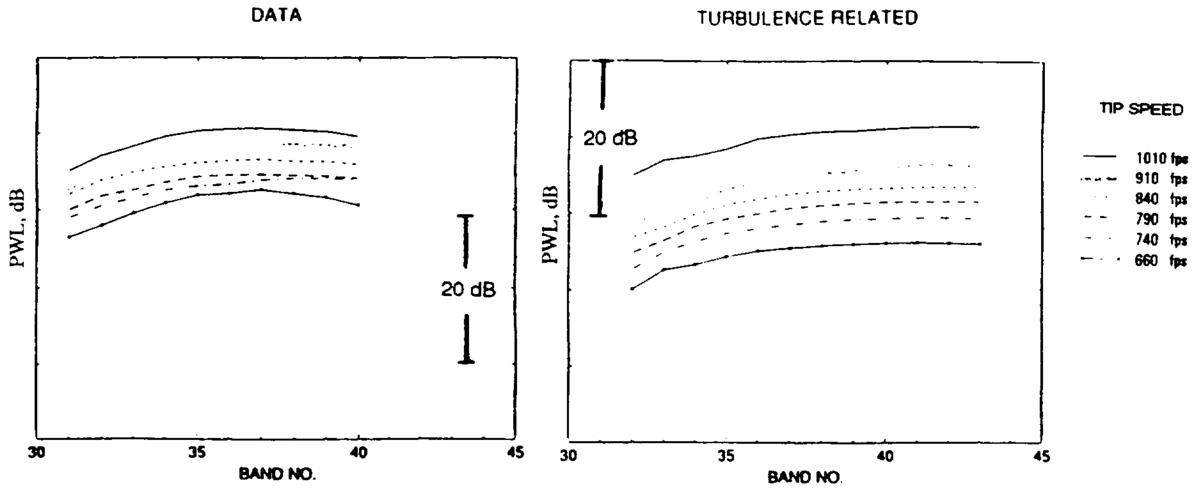


Figure 11a Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise from all the turbulence related mechanisms: Engine 4

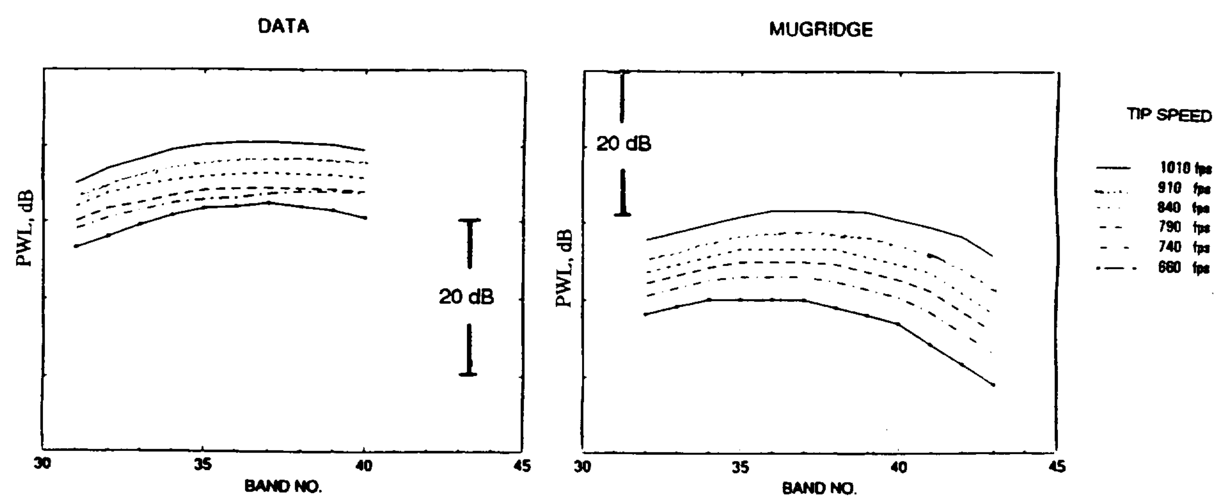


Figure 11b Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise (from rotor and stator) from turbulent boundary layer noise formulae of [8]: Engine 4

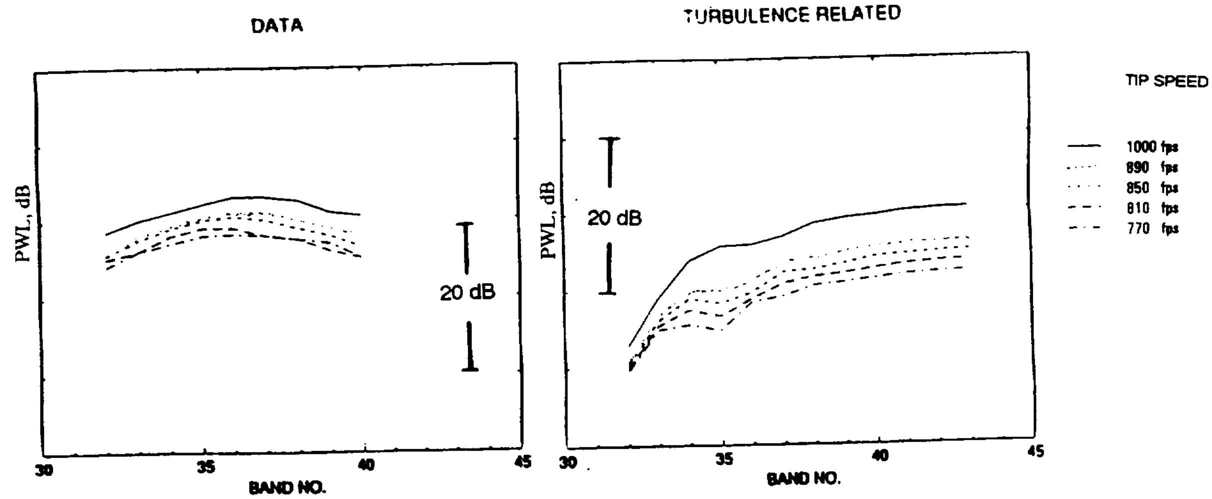


Figure 12a Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise from all the turbulence related mechanisms: Engine 5

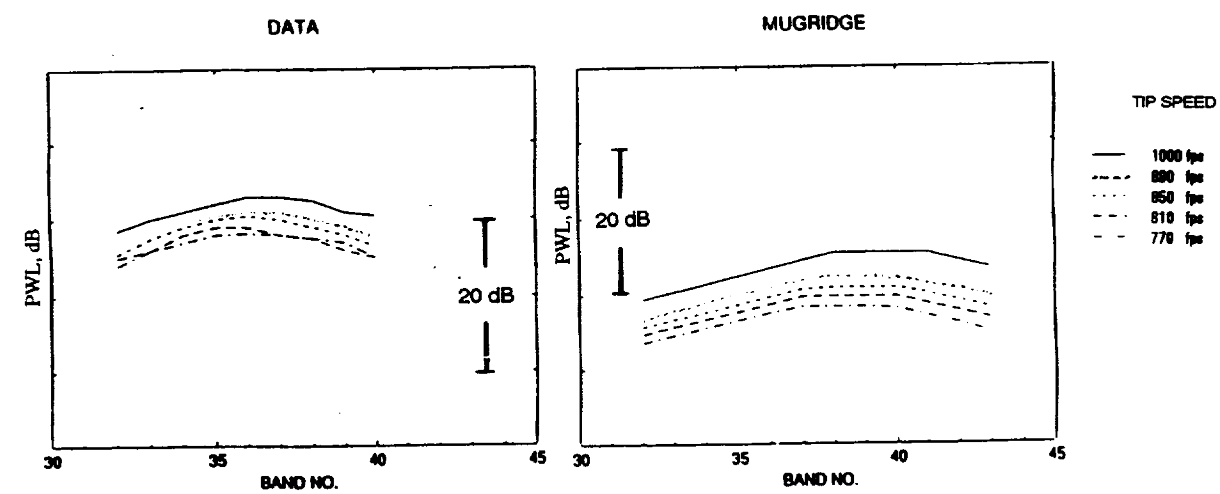


Figure 12b Theory–data comparisons for total third octave PWL spectrum (inlet + exhaust) versus octave band number: prediction (on right) is for total noise (from rotor and stator) from turbulent boundary layer noise formulae of [8]: Engine 5

Figure 13 shows a breakdown of the three mechanisms related to turbulence-blade row interactions, for the 2700 rpm case of Figure 10a. Similarly, The Mugridge [6] boundary layer turbulence mechanism "breakdown" for the contributions from the rotor row and the stator row are shown in figure 14. It can be seen from figure 13 that the inlet boundary layer turbulence-rotor interaction mechanism is the dominant source for the prediction model assumed. Similarly, figure 14 shows that the rotor turbulent boundary layer noise is much greater than the stator boundary layer noise, but is still at least 10 dB lower than the inlet boundary-layer turbulence-rotor noise levels (see figures 3a, 3b).

Typical examples of the dipole and quadrupole contributions to the broadband noise produced by the fine-scale turbulence related blade-row interaction mechanisms are shown in figure 15. It can be seen that the quadrupole mechanism is clearly the most important at high frequencies.

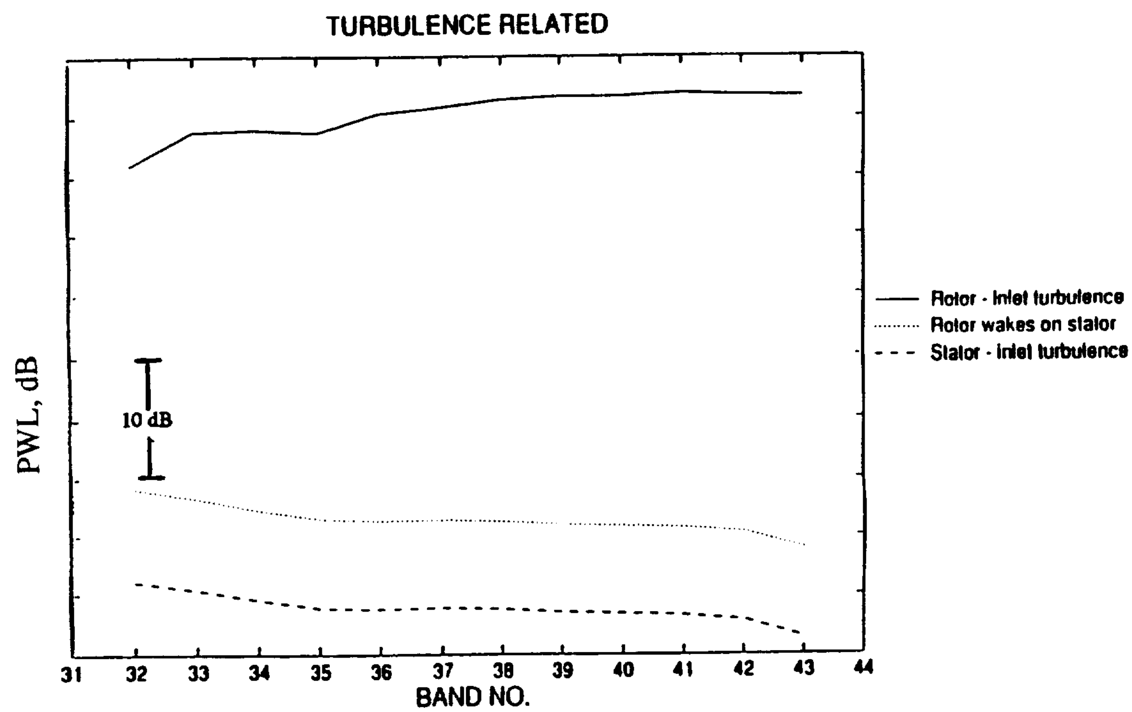


Figure 13 **Breakdown of contributions to PWL spectrum by various turbulence related mechanisms for a typical case–theoretical prediction**

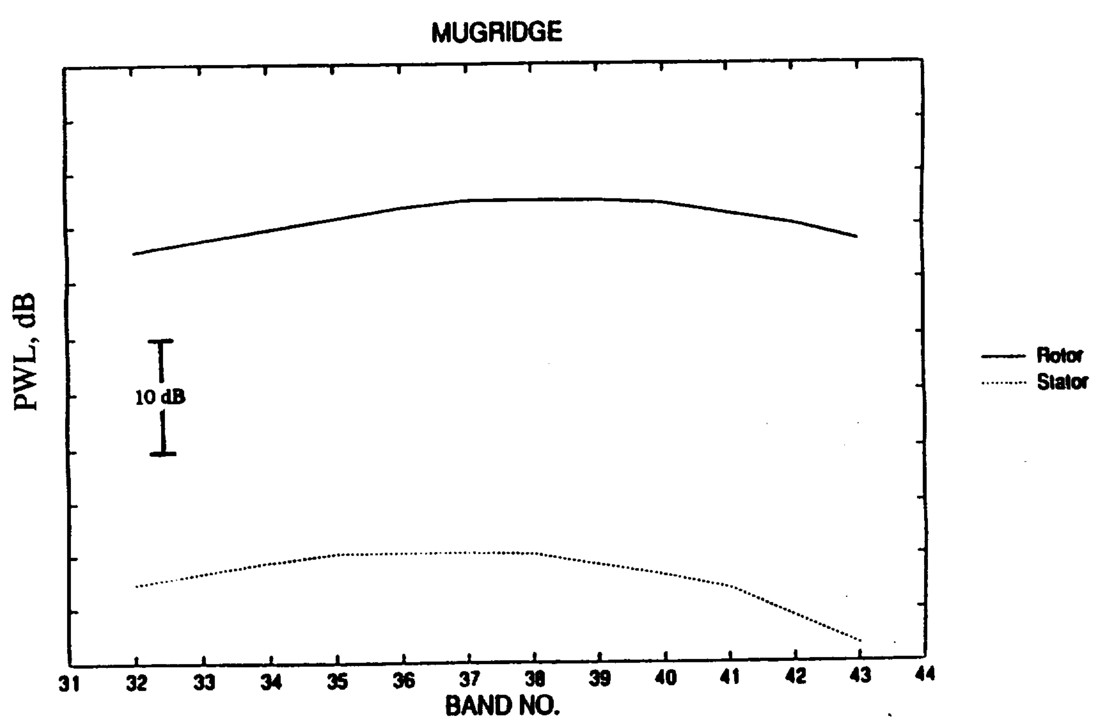


Figure 14 **Breakdown of turbulent boundary layer noise contributions from rotor and stator blade rows according to formulae of [8]**

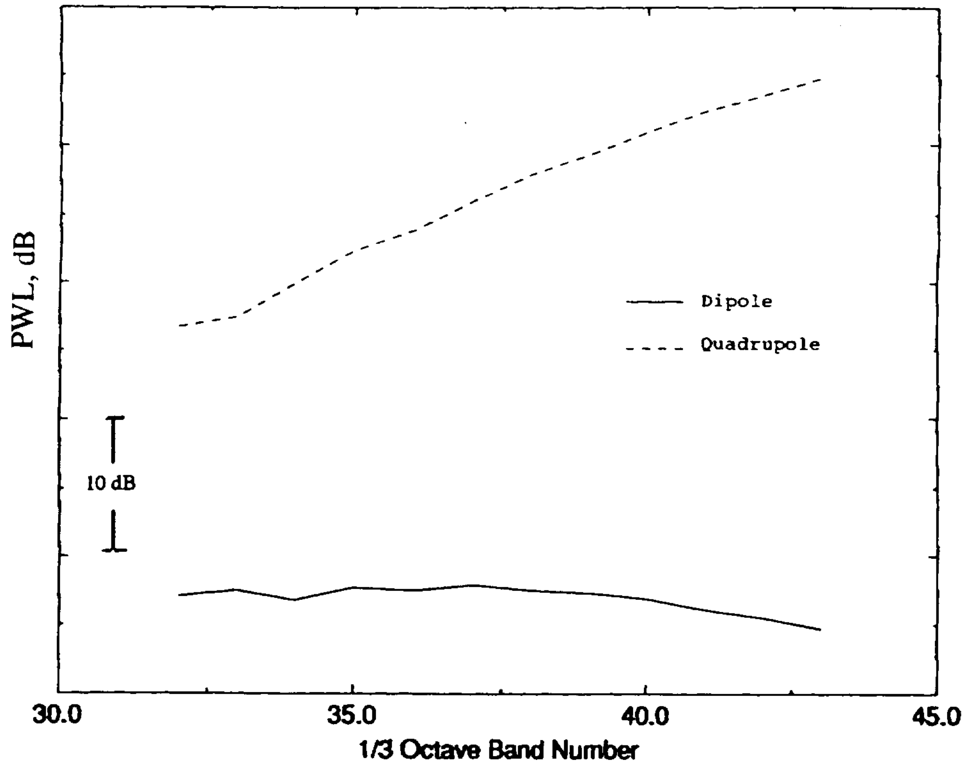


Figure 15a Inlet Noise: Dipole and Quadrupole Contributions

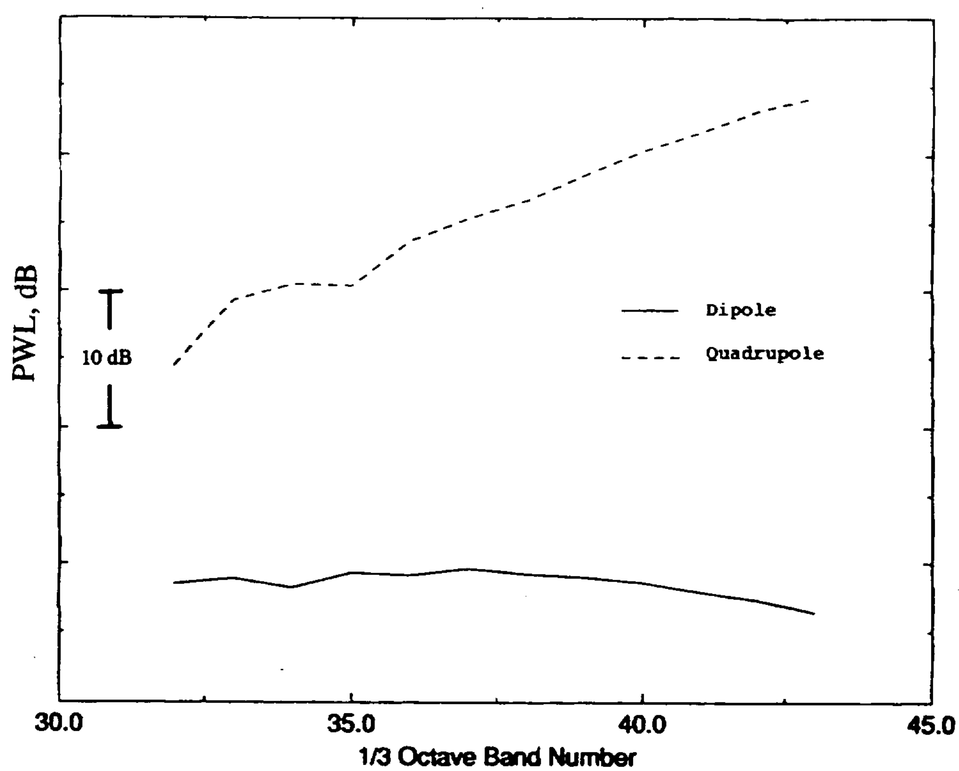


Figure 15b Exhaust noise: Dipole and Quadrupole Contributions

8.0 RECOMMENDED EXPERIMENTAL PROGRAM

8.1 Experimental Program Needs and Objectives:

From the results obtained in the present study, as summarized in Sections (4-7), a well-planned experimental program is needed to provide the necessary model prediction input and validate and calibrate various model features. In addition, a systematic data base would be extremely useful in quantifying the key broadband mechanism controlling parameter effects and providing guidance in improving existing theoretical models. Acoustically, test configurations have to be selected so that broadband noise levels can be varied in a controlled environment. The experimental program should provide for conditions that would allow demonstration of broadband noise increases as well as reductions. Turbulence and other non-steady-state aerodynamic data must be measured for use in acoustic calculations and prediction calibration. Aerodynamically, the mesurement has to include both time-averaged as well as time-varying velocities, both in front of and aft of the rotor.

In engine tests, low frequency broadband noise may be contaminated by jet noise, and therefore every effort must be made to avoid the fan noise data being masked. Hence a scale model fan rig becomes the preferred testing device. In order to provide the flexibility for aerodynamic, acoustic and operability assessments, an air-driven scale model propulsion simulator is desirable. Model size or scale factor is a critical issue, since the broadband noise mechanisms are likely to be sensitive to Reynolds Number (turbulence scales, boundary layer thicknesses, etc.). The model size affects the choice of test facilities and the cost of test programs, while the scale factor determines the level of uncertaintites for projecting the results to full size fan/engine.

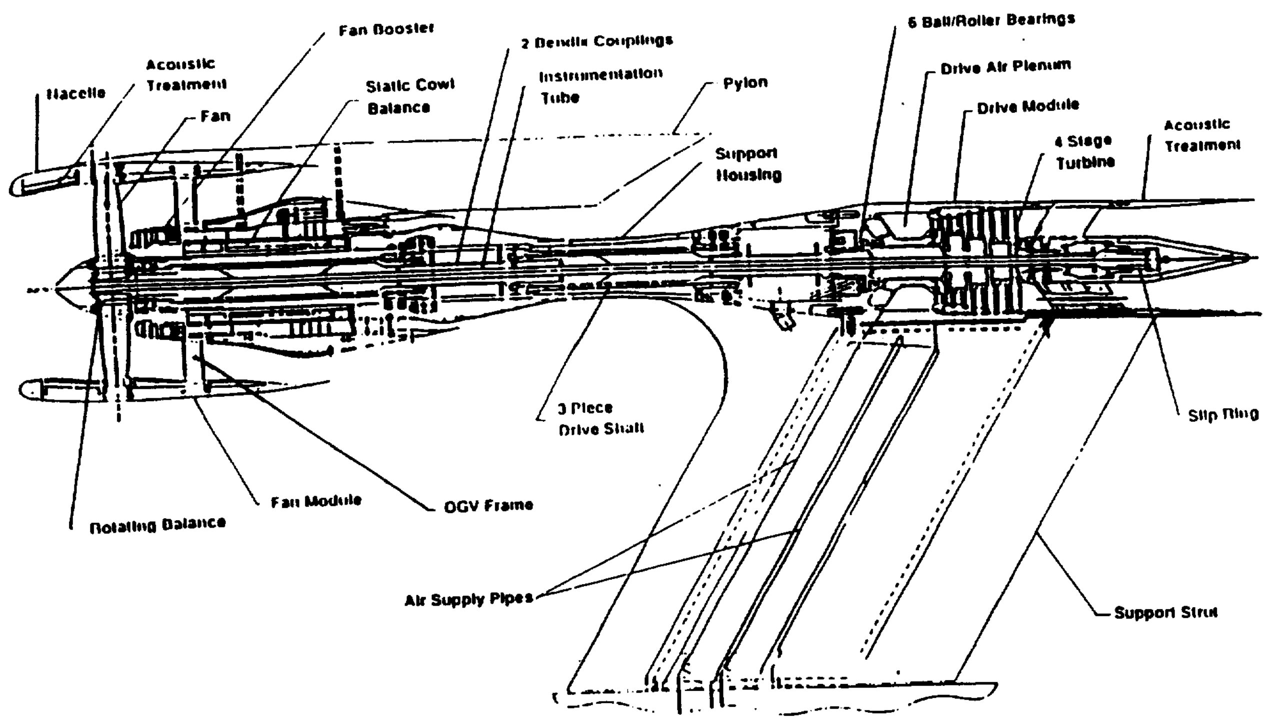
A scale model propulsion simulator, such as that described in reference [51], typically preserves the Mach Number related parameters, including fan tip speed, pressure ratio, and specific weight flow (flow per unit annulus area). However, the smaller the model, the lower will be the simulated Reynolds Number. A smaller model also requires smaller instrumentation to reduce rake blockage, or otherwise the probes may modify the flow field. For acoustic analysis, an upper limit on measurement frequency of 10 KHz is required for a full size engine, and so any scale model test requires having a useable measurement frequency range of (inverse of scale factor) multiplied by 10 KHz. For example, a 1/6th scale model would require scale model test measurements up to 60 KHz. Small scale factors will demand high resolution acoustic data processing, large amounts of data, and will be subject to the limitations of available data acquisition and processing equipment. In addition, for very small scale models, noise sources of interest can be masked by noise caused by flow field disturbances introduced by objects, steps or unevenness in hardware on the order of a tenth of an inch, affecting or contaminating the noise spectrum in the 60 to 100 KHz frequency range. Finally, hardware manufacturing tolerances, and sensitivity of performance measurement equipment can be limiting factors for small scale rig data accuracy. On the other hand, choosing an an overly large model can lead to excessive power requirements and high costs in both hardware and facility operation. A detailed discussion of these scaling issues can be found in References [51,52].

From the point of view of carrying out diagnostic measuremnets, the capability for manipulating boundary layer turbulence is desirable. This can be accomplished by testing several inlet lengths, in the case of rotor inlet boundary layer turbulence, for example, or by changing inlet surface roughness or employing inlet boundary layer suction and blowing devices. The capability of varying fan loading at constant tip speed is desirable, since it has been identified that broadband noise empirically correlates with rotor inlet incidence angle. This can be accomplished by employing a variable-area fan nozzle, or by testing with several nozzles of different areas. The fluctuation characteristics and statistical properties of turbulence can be measured using a 2-dimensional hot wire / film probe in front of and behind the fan blades, and in front of the OGV's. In addition, a non-intrusive surface measurement of unsteady flow properties may be useful, employing a Senflex Sensor, for example, which can be pasted on blades and vanes.

In summary, a controlled-environment experimental investigation is required on a scale model fan that is a reasonably good aerodynamic simulation of full-scale engine fans, from the point of view of Mach number, Reynolds number and hardware quality and surface finish and integrity. The model simulation should be large enough to provide minimal disturbance to the aerodynamics when diagnostic measurements are made with intrusive instrumentation. The experiments should include high-quality far field acoustic measurements, both narrowband and third-octave, and thorough aerodynamic surveys of both steady and unsteady flow upstream and downstream of both rotors and stators. The experimental investigation should provide for controlled variations in inlet and blade wake turbulent boundary layer characteristics, and should include surveys of these characteristics, using the latest hot-wire/film techniques. A wind tunnel test program is desirable, using a propulsion simulator such as that described in references [51,52]. It may be possible to limit wind tunnel velocity to low ($M_0 \sim 0.1$) and still achieve reasonably smooth, low-turbulence inflow conditions. Alternatively, a Turbulence Control Screen (TCS) could be employed and much of the measurements could then be made without forward speed, or in an anechoic chamber. One issue here, however, is whether or not the inlet boundary layer characteristics are properly simulated without forward-flight simulation.

8.2 Scale Model Fan Test Plan Recommendations:

Figure 16 shows the GE Universal Propulsion Simulator (UPS) recommended for meeting the test objectives discussed above. It has a 22-inch diameter fan, the data from which can be scaled up to full size engines from 4 ft. to 11 ft. in diameter while staying within the reasonable frequency range of 0-60 KHz. Most importantly, the measured performance data can be directly scaled up to full size without worrying about rake/probe blockage.



Note: "NACELLE MODULE" shown rotated 90° for clarity

Figure 16 GE Universal Propulsion Simulator (UPS)

Turbulence measurement equipment developed by GE can be easily adapted to take appropriate turbulence/flow fiield measurements in the UPS flow path at operating conditions of interest. Hot film probes can be placed in front of the fan inside the inlet duct to measure both wall boundary layer turbulence and free stream turbulence. Probes can be placed behind the fan rotor and in front of the OGV's to measure the rotor wake turbulence and its axial decay inside of the fan casing. Time-averaged data as well as time-history of the fluctuating velocities are required for the caluculation of turbulence parameters relevant to validation or calibration of acoustic models such as those of [5,6,7,8,16,22,28].

In addition to the non-steady state parameters, steady state aerodynamic information can be obtained through a data-match process, utilizing steady-state probe and rake total pressure, temperature and flow angle data. This matching process utiilizes a circumferentially-averaged flow analyis code called CAFD, which generates the streamline flow vector diagrams and blade and vane turning and loss characteristics, based on "matching" the measured total pressure and temperature profiles and duct wall static pressures. This is useful for providing aerodynamic parameters as input to acoustic models. It is recommended that the aerodynamic surveys be done separately from the acoustic measurements, as rakes and probes in the flow can cause excess noise.

The following test program configuration matrix is recommended for diagnostic evaluation of fan broadband noise mechanisms:

1. Test an isolated rotor on the UPS to identify the inlet boundary-layer turbulence-rotor interaction component of the fan broadband noise spectrum. A special fan frame and external support assembly will be required to hold the fan duct and nacelle without downstream OGV's or struts. Vary inlet boundary layer thickness and turbulence level by using various combinations of inlet length and inlet surface roughness and/or vortex generators. Vary rotor loading by using a variable area nozzle or testing with three nozzle sizes.

2. Test a rotor-stator combination, and vary the axial spacing of the stator (OGV), to assess the effect of rotor wake decay and diffusion on the OGV-related broadband noise. The external nacelle support assembly may be required for this test, to allow changing the OGV axial position without being hampered by internal support strut locations. Vary rotor wake turbulence intensity and thickness by adding boundary layer trips and/or fences and/or vortex generators on to the blade surfaces. It is recommended that this be done in radial zones, i.e., "hub region," "pitchline region," and "tip region," to evaluate the important areas of fan OGV-generated broadband noise.

3. Test a range of rotor tip clearances (e.g., "tight", "nominal" and "open") with a rotor-OGV combination, to assess the influence of rotor tip clearance on broadband noise. This should be done with two or three inlet boundary layer thicknesses evaluated in

configuration 1 above, to establish the relative interaction between inlet duct boundary layer flow and tip clearance flow and the resultant impact on fan broadband noise.

4. Once the test results of the above configurations have been analyzed, a test of two or three candidate noise reduction concepts on the UPS is recommended. This could be done in a "Phase 2" or second test series, along with any other diagnostic testing that may suggest itself after the first test series has been analyzed. From the test results of these two or three concepts, a final concept could be selected for validation on a full-scale engine.

A full compliment of aerodynamic steady-state and unsteady measurements should be made on the above recommended configurations, as described in the introductory paragraphs, so that a complete tie can be made between the aerodynamic flow fields and turbulence properties and the resulting fan broadband noise spectral characteristics.

8.3 Engine Test Validation Plan Recommendations:

The requirements for engine demonstration/verification of broadband noise generation mechanisms are the same, but the test program need not be nearly as extensive as for the scale-model UPS rig program. Static testing must be done with a Turbulence Control Screen (TCS) such that atmospheric inflow turbulence-rotor interaction noise can be alleviated/eliminated. In addition, a large acoustic barrier should be installed to seperate inlet from exhaust radiated noise, and vice versa. Static engine noise tests are usually carried out in an outdoor, open field arena on hard flat surface (concrete or blacktop) at a distance of 20 or more times fan radius, and 5 or more wavelengths away from the lowest frequency of interest.

GE has a CFM56-3 engine fitted with a 60-inch diameter, wide-chord fan available for testing. The fan blades are of the same family as the wide chord fan blades previously tested on the UPS rig and a similar design is currently being utilized on a larger size engine. The UPS fan is approximately 1/3-scale and 1/6-scale for these two engines.

The objective of an engine test is to provide a direct comparison between scale model and full size aerodynamic and acoustic characteristics for a modern, new-technology fan. The advantage of using a scale model , a "half-size" engine, and then a "full size" engine is to be able to sort out the possible scaling relationships for broadband noise for fans with similar Mach number but different Reynolds numbers based. Again, turbulence measurements in front of and aft of the rotor and OGV's would be useful on the engine tests as well, to first of all verify that the inlet boundary layer and rotor wake turbulence characteristics are dynamically similar for small and large scale, and for providing input to prediction models. The engine test can also validate fan broadband noise concepts derived from the UPS test data analysis and/or prediction model design studies.

It is therefore recommended that an engine test be carried out as a follow-on to the UPS rig test program. In order to vary the broadband noise in an engine, additional hardware to may be required to: (1) vary inlet length, (2) to provide inlet boundary layer blowing and suction capability, and (3) to vary fan nozzle area, to change the fan loading and rotor wake characteristics. The test should also include a configuration change that embodies a broadband noise reduction concept, which of course is yet to be defined. But this could come from the analysis of the UPS test program results, and could even be tested on the UPS rig prior to committing to full-scale engine hardware.

All that can be sufficiently defined at this time is the scale model diagnostic experimental program phase as described and recommended above. This information must come first in order to properly define any further noise reduction conept testing in model or full scale. Depending on existing availability, it may be prudent to acquire full-scale engine data on a "piggy-back" basis to provide at least some of the model-to-full scale validation information discussed above.

9.0 CONCLUSIONS

Based on the system study results reported herein, once fan tones are eliminated, fan broadband noise reduction can provide as much as 3 to 4 EPNdB reduction in engine system noise. Higher goals (7 to 10 EPNdB reduction) can only be achieved with a combination of moderate increases in engine bypass ratio and broadband noise reduction. Broadband noise levels for current technology engines appear to be related to rotor blade incidence angle and fan operating conditions. Broadband noise source reduction can be achieved by reduction of small scale turbulence fluctuations.

From the analytical model mechanisms assessment study reported herein, the dominant mechanism of broadband noise is the quadrupole noise mechanism due to interaction between fine-scale turbulence in the casing boundary layer and rotor tip sections. Whenever a quadrupole mechanism is dominant (as identified above), we can then expect (in this case) that, at fixed tip speed, the acoustic power would vary as (incidence angle)^2, or the decibel equivalent (PWL) should vary as 20 $\log_{10}$(incidence angle). The relevant incidence angle in this case is the incidence angle of the rotor.

The quadrupole noise mechanism varies as the lift coefficient, C_L. The lift coefficient may be expected to be an increasingly strong function of incidence angle as the relative Mach number to the blade row approaches unity. Thus the dependence of noise on incidence angle may itself be expected to increase as the relative Mach number approaches unity.

In so far as the Mugridge formulae [8] do represent blade and vane turbulent boundary layer noise, this noise mechanism does not appear to be a significant contributor to the total fan broadband noise spectrum.

Both the theoretical predictions involving turbulence-related mechanisms and those based on the Mugridge formulae tend to over predict the variation of noise due to tip speed.

10.0 RECOMMENDATIONS

Further work is needed both in analytical and experimental areas. Refined analytical modeling of blade and vane interaction with turbulence needs to be carried out. Experimental measurement of fluctuating flow field should be done to provide aero input to acoustic model. Verification test should follow to demonstrate quantitatively.

Recommendations for future work

1. The analysis method [8] for the rotor–inlet turbulence quadrupole noise mechanism requires extension to supersonic tip speeds (more precisely, supersonic rotor inlet relative Mach numbers)

2. The efforts to deduce rotor wake turbulence properties from its drag coefficient need to be re–examined in view of indications (according to present calculations) that this is not a serious source of broadband noise. The method currently used to simplify the modeling of rotor wake turbulence–OGV interaction noise source as one amenable to prediction via notions of homogeneous, isotropic turbulence interacting with the outlet guide vanes also needs re–examination.

3. The theory data comparisons of Figures 8-12 suggests that the theoretical predictions do not adequately capture the high frequency fall off of the data. This could be due to a failure to account for source non-compactness effects in calculating the steady potential flow associated with the rotor (needed for evaluation of the quadrupole noise). Source non-compactness of the quadrupole noise source term itself is fully accounted for in the current calculations. An extension of the present model [8] to include this effect is recommended.

4. It is recommended that a study be undertaken to explore whether using an anisotropic model of turbulence along with some approach to filtering out "pure tones" in the predictions (as is done with the data) produces better agreement with the spectral shape of the broadband noise as measured.

5. A more thorough exploration of whether [8] provides a truly quantitative estimate of turbulent boundary layer noise should be carried out. Also, as mentioned earlier, suitable quantitative estimates of vortex shedding noise have not yet been located.

6. We need to establish further whether blade loading (or incidence angle) and tip speed effects are being correctly captured by the present analysis or its extensions (as suggested

above). There is evidence that the present results overestimate the variation of noise with tip speed.

7. Whether by experiments involving inlet boundary layer suction or by more careful assessment of the separate contributions of the rotor and of rotor–outlet guide vane interaction to the broadband noise, it is necessary to corroborate or disprove present analysis results that the dominant broadband noise mechanism is the rotor–inlet boundary layer turbulence interaction (particularly the quadrupole component of this interaction).

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13. ABSTRACT *(Maximum 200 words)*

A study has been completed to quantify the contribution of fan broadband noise to advanced high bypass turbofan engine system noise levels. The result suggests that reducing fan broadband noise can produce 3 to 4 EPNdB in engine system noise reduction, once the fan tones are eliminated. Further, in conjunction with the elimination of fan tones and an increase in bypass ratio, a potential reduction of 7 to 10 EPNdB in system noise can be achieved. In addition, an initial assessment of engine broadband noise source mechanisms has been made, concluding that the dominant source of fan broadband noise is the interaction of incident inlet boundary layer turbulence with the fan rotor. This source has two contributors, i.e., unsteady life dipole response and steady loading quadrupole response. The quadrupole contribution was found to be the most important component, suggesting that broadband noise reduction can be achieved by the reduction of steady loading field-turbulence field quadrupole interaction. Finally, for a controlled experimental quantification and verification, the study recommends that further broadband noise tests be done on a simulated engine rig, such as the GE Aircraft Engine Universal Propulsion Simulator, rather than testing on an engine statically in an outdoor arena. The rig should be capable of generating forward and aft propagating fan noise, and it needs to be tested in a large freejet or a wind tunnel.

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